Management Strategy Evaluation in R (*mseR*): User's Guide and Simulation Exercises

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by

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ABSTRACT

Kronlund, A.R., Cox, S.P., and Cleary, J.S. 2012. Management strategy evaluation in R (*mseR*): user's guide and simulation exercises. Can. Tech. Rep. Fish. Aquat. Sci. 3001: vii + 52 p.

mseR, Management Strategy Evaluation in R, is a computer software package that implements a simple closed-loop feedback simulation of a fisheries management system. This version of *mseR* was developed to examine the linkages between fishery-independent surveys and a harvest control rule that translates assessment outputs into fishery regulations in the form of a total allowable catch. Closed-loop simulation models are an important component of management strategy evaluation because they allow examination of the effects of multiple sources of uncertainty on management performance.

RÉSUMÉ

Kronlund, A.R., Cox, S.P., and Cleary, J.S. 2012. Management strategy evaluation in R (*mseR*): user's guide and simulation exercises. Can. Tech. Rep. Fish. Aquat. Sci. 3001: vii + 52 p.

mseR, évaluation de la stratégie de gestion en programme informatique de R, est un logiciel informatique qui met en œuvre une simulation de rétroaction simple boucle fermée d'un système de gestion des pêches. Cette version de *mseR* a été développé afin d'examiner les liens entre les relevés indépendants des pêches et une règle de contrôle de la récolte qui se traduit par des sorties d'évaluation dans les règlements de la pêche sous la forme d'un total admissible des captures. Modèles de simulation en boucle fermée sont une partie importante de l'évaluation de la stratégie de gestion des pêches, car ils permettent d'étudier les effets de plusieurs sources d'incertitude sur la performance de ce gestion des pêches.

1 WHAT IS MANAGEMENT STRATEGY EVALUATION?

Management strategy evaluation (MSE) encourages a consistent approach to designing robust fishery management systems through extensive computer simulation (e.g., Walters 1986, de la Mare 1998, Smith 1993, Cooke 1999, Punt and Smith 1999, Sainsbury et al. 2000, Butterworth 2007). The consequences of a range of management strategies are assessed relative to stock and fishery dynamics, with emphasis placed on exposing the underlying trade-offs in a managers' ability to satisfy conflicting conservation and yield objectives. Closed-loop simulation models are an important component of MSE because they allow examination of the effects of multiple sources of uncertainty on management performance. Operational objectives are determined in consultation with fishery managers and stakeholders. Objectives for conservation and yield may reflect national and international policy commitments (e.g., Shelton and Sinclair 2008), constraints faced by managers, and specific statements by stakeholders that identify their interests for the conduct of the fishery. The software described in this report, called Management Strategy Evaluation in R (*mseR*), implements a simple closed-loop feedback simulation of a fisheries management system.

The MSE methodology is defined by four components: (*i*) operational objectives, (*ii*) specific fishery monitoring data and stock assessment methods, (*iii*) harvest control rules that relate estimates of stock status to catch limits, and (*iv*) a prospective evaluation of the entire procedure using a set of performance statistics (de la Mare 1996). Operational objectives represent the translation of goals for the stock and fishery into measurable outcomes to be achieved with a specified certainty within some agreed upon time frame. Data collection, stock assessments, and harvest control rules represent the decision-making framework or management strategy whereby scientific information is collected, processed, and used in setting fishery regulations (e.g., annual catch limits). The terms management strategy and management procedure are used interchangeably. The performance statistics relate directly to objectives, which are typically cast in terms of conservation, yield, and yield volatility (i.e., stability) metrics.

The technical basis of MSE is a computer-based facsimile of the management system that simulates the annual processes of data gathering, stock assessment, and application of the harvest control rule. These elements are presented schematically as Figure 1. At each successive annual step the resultant harvest advice, usually in the form of a total allowable catch (TAC) recommendation, is applied to an operating model that represents stock and fishery dynamics. The operating model also generates the following year's survey and fishery data such as abundance indices, biological data, and catch, i.e., data that can actually be collected by the management system. Progressive iteration of this process will provide feedback into future management decisions by reducing the TAC when survey abundance indices trend downwards in an attempt to reverse the declining trend towards some pre-specified desirable management target. Conversely, feedback control acts on the management system to increase TAC recommendations when survey indices trend upwards. In addition to corrective actions in response to declines in stock size, feedback control can also act to self-correct erroneous perceptions

about the current status of the resource. Such perceptions can result from uncertainty in determining stock status or from structural misspecification between the true dynamics represented by the operating model and those specified in the assessment method.

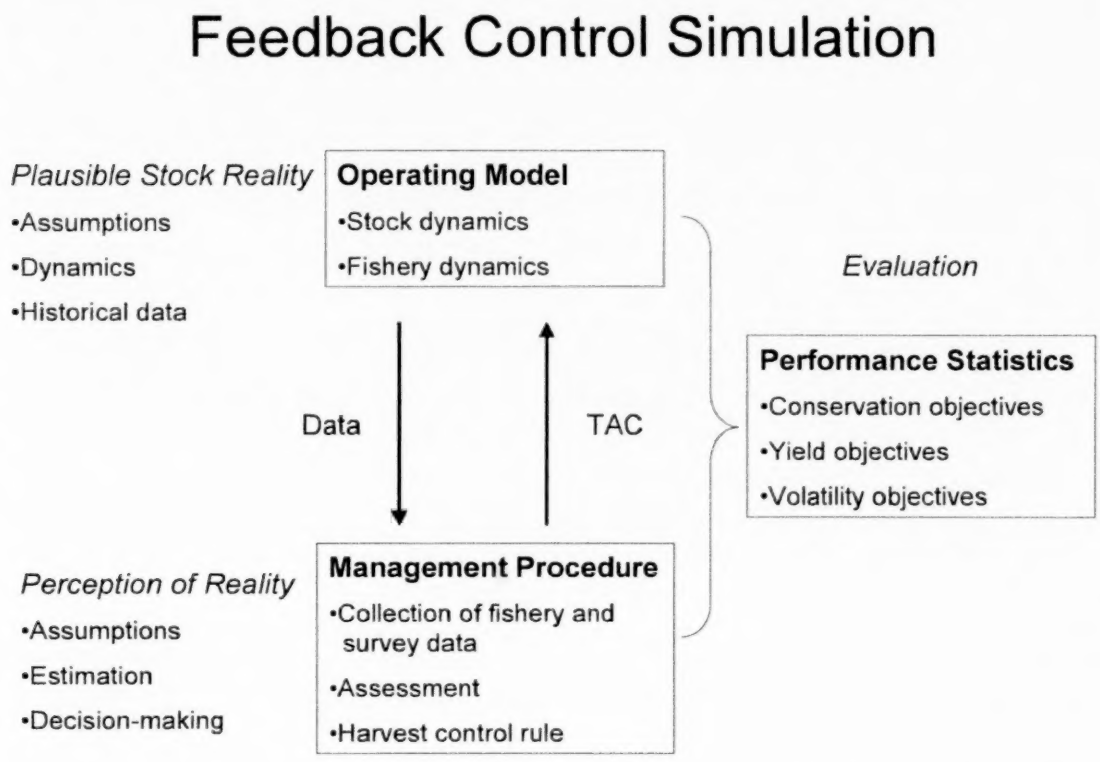

Figure 1. Schematic representation of a feedback control simulation for fisheries management.

2 TERMINOLOGY

Describing the *mseR* software requires a basic set of terminology related to the underlying management strategy evaluation methodology. In some cases, **bold font** will be used in subsequent sections of this document to indicate that a term can be referenced back to this section.

Feedback control: A relationship between variables in a system where the consequences of an event are input back into the system, modifying the event in the future. In fisheries, feedback control is achieved by rules based directly or indirectly on trends in resource indices, which adjust the value of management measures such as total allowable catch (TAC) in directions intended promote stock abundance towards desirable levels.

Harvest control rule (HCR): A set of well-defined rules used for determining a management action in the form of a total allowable catch (TAC) or allowable fishing

effort given input from a stock assessment estimator, or directly from data. Also called a **decision rule** or **harvest strategy**.

Limit reference point (LRP): The stock level threshold below which productivity can be impaired enough to cause serious harm to the fishery resource and below which the fishery removal rate is reduced to the lowest possible rate. In the Canadian policy context, this reference point should be above the level at which a stock will become at risk of extinction (DFO 2006).

Management procedure (MP): The combination of data collected according to pre-defined sampling protocols, an **assessment method** for estimating stock status using those data, and a harvest control rule that translates the outputs of the assessment method into a total allowable catch (TAC) or an effort control measure. Additional tactics may be included in the procedure such as spatial or seasonal closures, gear restrictions, or size limits. Two types of MP may be distinguished:

> **Model-based MP**: A MP where the process used to generate a control measure such as a TAC is a combination of data, a stock assessment model estimator (e.g., catch-at-age model, surplus production model, etc.) and a HCR;
>
> **Empirical MP**: A MP where resource-monitoring data, such as survey estimates of abundance, are input directly into a harvest control rule that generates a control measure such as a TAC without an intermediate estimator, i.e., the assessment method is the survey estimator of abundance.

Operating model (OM): A mathematical-statistical model used to describe the actual fish population and fishery dynamics in simulation trials and to generate resource monitoring data when projecting forward in time.

Performance statistics: Statistics that summarize different aspects of the results of a simulation trial. Performance statistics are used to evaluate how well a specific MP achieves some, or all, of the pre-specified objectives for management.

Removal reference: The maximum removal rate (e.g., harvest rate) allowed by the harvest control rule given the stock status. The highest removal rate is permitted when the stock status is determined to be above the Upper Stock Reference point. *mseR* uses a removal rate of zero when stock status falls below the LRP.

Replicate: One realization of an operating model scenario projected forward in time for a specified period, under controls defined within a MP. A large number of replicates will typically be conducted to capture stochastic effects.

Scenario: A specific hypothesis concerning resource status and dynamics, represented mathematically as an OM.

Trade-offs: Comparisons of gains in some performance statistics against losses in others when selecting among competing MPs; these trade-offs arise because some objectives for management conflict (e.g., maximizing catch versus minimizing risk of stock depletion).

Upper stock reference point (USR): The stock level threshold below which the removal rate is reduced according to the harvest control rule used in *mseR*. The value of this reference point is based on fishery objectives, which can include biological, social, and economic factors (DFO 2006).

3 WHAT IS *mseR*?

Management Strategy Evaluation in R, or *mseR*, is a computer software package that implements a simple closed-loop feedback simulation of a fisheries management system. The software is based in the statistical computing language R (R Development Core Team 2006). This version of *mseR* was developed to examine the linkages between fishery-independent surveys and management advice. Surveys are frequently important determinants of fisheries management decisions and typically represent a significant component of the overall cost of the management system. Furthermore, the fishing industry and other stakeholders (e.g., First Nations and recreational fishermen) often have suitable expertise, vessels and gear to conduct the work, and a keen interest in supporting surveys because of their direct connection with the resource. However, their investment in survey activities may be contingent on analysis of the expected gains, whether those gains are measured in terms of economic yield or assurance that conservation issues will be avoided in keeping with the Precautionary Approach principles of resource management (FAO 1995).

One approach to evaluating the question of survey utility is to use closed-loop feedback simulations of the specific *management system* (Walters 1986, Cooke 1999, de la Mare 1986, 1996, 1998, Butterworth 2007). The premise is that the properties of a survey can only be fully examined by evaluating it 'in-place', i.e., in a reasonable facsimile of the context in which it is to be used. The technical exercise of simulation becomes management strategy evaluation when coupled with an iterative and consultative process of setting objectives and evaluating system performance. The *mseR* software allows exploration of the situation where an existing survey is altered, perhaps in frequency of occurrence or by the amount of effort allocated to the survey. The affect of transitioning from an old to a new survey is also dependent on the choice of stock assessment method and the harvest control rule. *mseR* integrates these factors into a feedback control simulation which allows the management procedure to be evaluated as a system relative to fishery objectives.

The *mseR* operating model described in Appendix A is used to determine a stock reality consistent with specified assumptions and historical data. The operating model determines the corresponding population dynamics of the fish stock and the interaction of the fishery with the fish stock. The management procedure is blind to the assumptions and structural specification of the operating model and can access only the survey, fishery

and environmental data that can actually be observed. These data are input to the assessment method and the outputs are used to determine a management action using a harvest control rule as described in Appendix B. The procedure provides feedback to the operating model in the form of a TAC. Performance statistics related to conservation, yield and volatility objectives are compiled to evaluate the success of the procedure (Appendix C, Section 5.4).

mseR software functionality is divided into three components, each of which is associated with a graphical user interface (GUI) control based on the R package *PBS Modelling* (Schnute et al. 2010):

1. ***mseR* Simulation Control** GUI or *guiSim*: Controls the specification and stochastic simulation of fish population dynamics, fishery-independent survey dynamics, and a harvest control rule;

2. ***mseR* View Control** GUI or *guiView*: Allows graphical inspection of the results of each replicated random realization of a stochastic simulation;

3. ***mseR* Performance Statistics Control** GUI or *guiPerf*: Computes statistics used to compare the relative performance of different simulations of the management system.

The three GUIs (1-3) are invoked by the commands `guiSim()`, `guiView()`, and `guiPerf()` entered at the R command-line console. All other user inputs are via keyboard and mouse-driven GUI operations. The sequence of *guiSim*, *guiView*, and *guiPerf* is typically the order of GUI usage required to create simulations of a management system and to evaluate the simulation results.

The ***mseR* Simulation Control** GUI allows the user to specify the required inputs and invoke the feedback loop function `runMSE()`. We use the following algorithm:

1. Define a management procedure based on (a) data types, (b) **assessment method**, and (c) **harvest control rule**;

2. Initialize a pre-conditioned **operating model** scenario that allows the user to specify the stock depletion at the start of the simulation;

3. Project the population and fishery dynamics one time increment into the future using the operating model, in this case one year. At each time increment apply the following sequence of sub-steps:

    a. Generate the data (1a) available for stock assessment;
    b. Apply the stock **assessment method** (1b) to the data to estimate quantities required by the harvest control rule;
    c. Apply the **harvest control rule** (1c) to generate a catch limit;
    d. Update the operating model population given the fishing mortality rate generated by the catch limit and new recruitment;

e. Repeat Steps 3a-3d until the projection period ends.

4. Calculate quantitative **performance statistics** for the simulation replicate;

5. Repeat Steps 2-4 over a specified number of **replicates** (e.g., 100 times) to accommodate uncertainty.

4 INSTALLATION

The statistical software language called R is a creation of the R Development Core Team (2006). Freely available, R provides a rich environment for problem-solving that is well-suited to fisheries applications. Furthermore, the R environment is designed to support user-contributed packages available from the R Archive Network (CRAN: http://cran.r-project.org/). The R base package, version 2.8.x series, was used for the development of *mseR* although subsequent releases should also work. The R base package can be installed as follows:

1. Find the R site at (http://cran.r-project.org/)
2. Under the heading "**Download and Install R**" press the "**Windows**" link
3. On the "**R for Windows**" page press "**base**"
4. On the "**R-2.x.x for Windows**" page press "**R-2.x.x-win32.exe**", where **x.x** represents the current release of R, to start the install and follow the directions.

The *mseR* software requires two R packages, *RODBC* (Lapsley and Ripley 2009) and *PBS Modelling* (Schnute et al. 2010). Note that *RODBC* is not supported under 64-bit Windows operating systems. After the R base package is installed, the required libraries can be added as follows:

1. Start an R session by double-clicking on the R desktop icon;
2. Set an R software distribution site by selecting the "**Packages**" menu item and "**Set CRAN mirror...**"
3. Again, select "**Packages**" then select "**Install package(s)...**"
4. Highlight "**PBSmodelling**" in the select list and press "OK"
5. Repeat step 3 and highlight "**RODBC**" and press "OK"

Use of the R language is greatly enhanced by the freely-available text editor called Tinn-R. This editor is sensitive to R-language syntax conventions. The Tinn-R editor can be found at http://www.sciviews.org/Tinn-R/. The **old stable version** (1.17.2.4) of Tinn-R is recommended. This is the default text editor required for *mseR* and must be installed to allow specific menu operations to function correctly.

The *mseR* software is supplied as a compressed file called *mseRv2.zip* and can be obtained by contacting the first author of this report. When the zipped file is extracted, the *mseR* folder will be created. The directory contains a file called *.Rdata* which is an R working directory. To start an R sessions, view the *mseR* folder using Microsoft Explorer

and "double-click" on the *.Rdata* file. This action will start the R command-line console where R language or user-written function statements can be entered, including the *mseR* GUI controls. The R language source files required to use *mseR* are listed in Table 1. At the R command-line console, type the command, `source("mseR.r")`, and press the <Enter> key to ensure all functions stored in R are consistent with the source files.

Table 1. List of R language source files required to use *mseR*.

R Source File	Description
mseR.r	Convenience file for easy "source" updating of *mseR* functions.
mseRanimate_funs.r	Functions to animate selected plots of individual replicates.
mseRgui_funs.r	Functions to display GUIs, validate parameters, file input/output.
mseRplot_funs.r	Functions to create and annotate plots.
mseRrefpt_funs.r	Functions to calculate fishery reference points.
mseRsim_funs.r	Functions to implement closed-loop simulation.
mseRstat_funs.r	Functions to calculate performance statistics.
mseRsurvey_funs.r	Functions to support survey spatial dynamics.
survRun.r	Support functions for survey spatial dynamics.

5 HOW TO USE *mseR*

5.1 OVERVIEW

Simulations can be specified, and the results inspected and compared, using a sequence of three steps as described below and presented schematically as Figure 2.

Step 1: Simulate the population and survey dynamics of interest by using the *mseR* function `guiSim()` to launch the *guiSim* control. This GUI allows a user to input parameter values and simulation conditions such as the number of years to simulate, the number of replicates and the labels used to identify the simulation.

Step 2: View the results of individual simulation replicates by using the *mseR* function `guiView()` to launch the *guiView* control.

Step 3: Compare the relative performance of different simulations by using the *mseR* function `guiPerf()` to launch the *guiPerf* control.

The *guiSim* control can load from a file, or save to a file, the set of parameters that completely specifies a simulation. The *guiSim* control also produces a set of plots to help visualize the effects of the specific parameter choices in the simulation related to life history, fishery reference points, and the harvest control rule. The simulation parameter file produced by *guiSim* is called *inputParameters.par*; it is read by the *mseR* function `runMSE()` when the feedback loop is called by pressing the <Run> button on the *guiSim* control.

The `runMSE()` function writes simulation tracking information to the *mseRsimTracker.txt* file and the actual simulation results are saved to an *Rdata* file named using the current date and time as determined from the system clock. One *Rdata* file is created for each simulation. The tracking file and simulation results are read by the *guiView* control which allows the user to choose from a variety of plots. Each *guiView* plot represents one replicate of a simulation. Similarly, the *guiPerf* control also reads the tracking file information and simulation results to allow the relative performance of the aggregate results of each simulation to be compared using plots and a table of performance statistics output to Microsoft Excel.

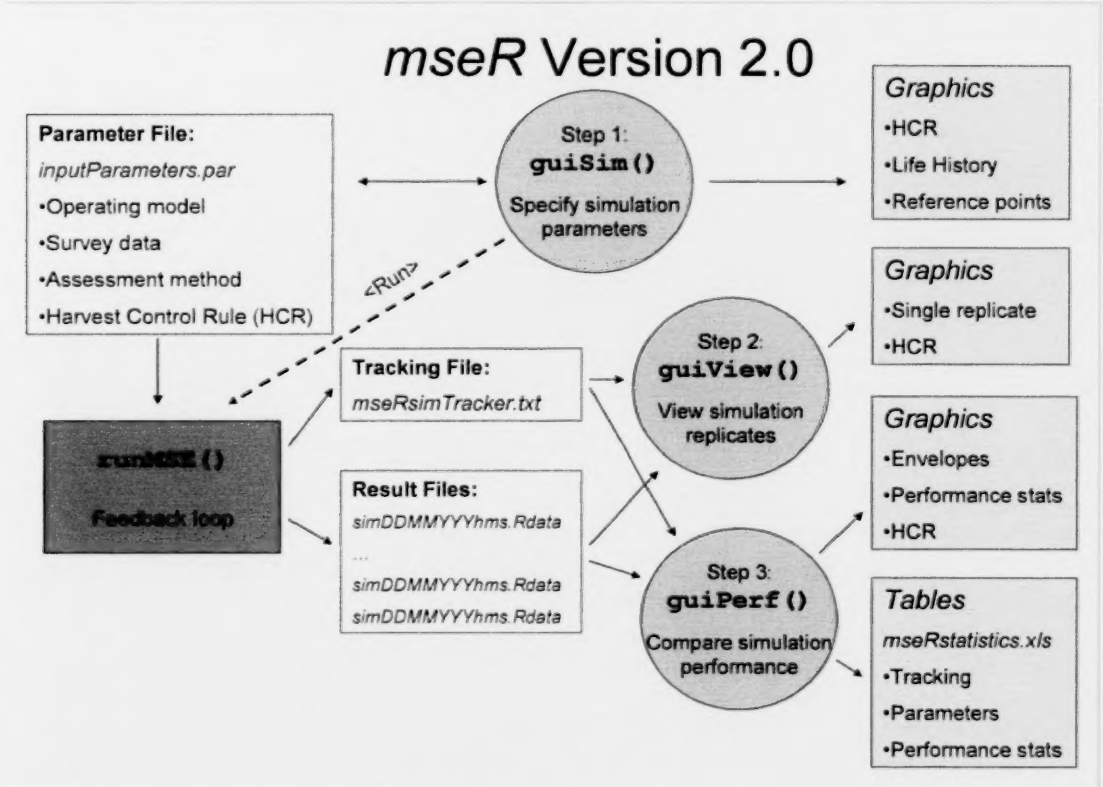

Figure 2. Schematic representation of *mseR* functions (blue circles), their inputs (white boxes) and outputs (yellow boxes). Feedback control is managed by the function `runMSE()`.

The three GUI controls are described in detail in the following sections, however, there are a few rules and general conventions for using the GUIs:

- Only one GUI can be active at a time. This behaviour is enforced by *mseR* to avoid some distressing Tcl/*Tk* effects on the graphics management of various windows;
- Entry fields that can be edited by the user are coloured with a white, yellow, or green background;

- Entry fields that report values and are intended to be "read-only" are coloured **pink**. Although these **pink** fields can be edited, changes have no effect on *mseR* operation;
- Non-numeric text fields can contain mixed alpha-numeric characters but should not contain spaces in the text;
- Note also that *mseR* will enforce range checking to ensure entry fields are valid and will report any errors to the R command-line console;
- In general, every menu has documentation and help available under pull-down top menu items <View> and <Help>.

5.2 *mseR* SIMULATION CONTROL (*guiSim*)

The ***mseR* Simulation Control** GUI (*guiSim*) determines all operating model and management procedure parameters (Figure 3). The control also provides a category of policy-based fields that allow stock status objectives to be specified and fields that report the operating model values of fishery reference points.

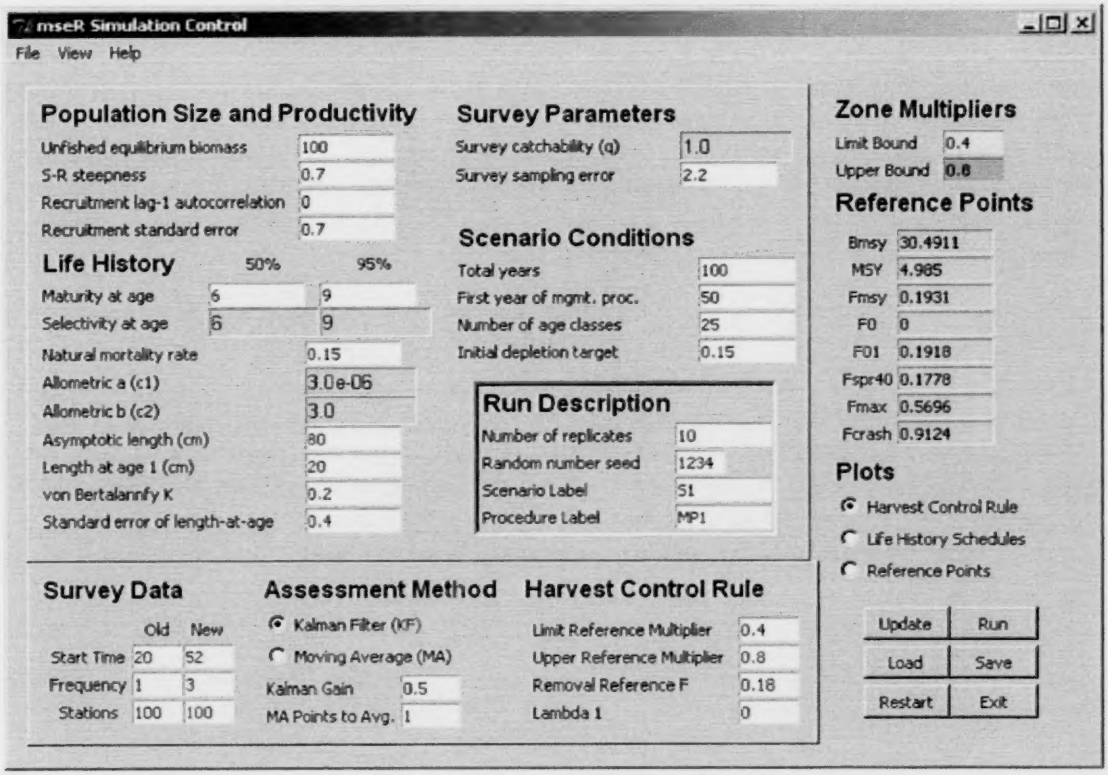

Figure 3. The *mseR* Simulation Control GUI.

The *guiSim* control consists of a suite of entry fields organized under field headers according to function (Table 2). Although most entry fields are self-explanatory and correspond to the model description in Appendix A and Cleary et al. (2010), the purposes

of selected fields are described in Table 3. The implications of current GUI settings can be displayed graphically by choosing the radio-button corresponding to the desired plot type under **Plots**. Six buttons located in the lower right corner of the GUI control simulation inputs and outputs (Table 4).

Table 2. *guiSim* control field header categories.

Category	Field Header
Operating Model	**Population Size and Productivity** **Life History** **Survey Parameters** **Scenario Conditions**
Management Procedure	**Survey Data** **Assessment Method** **Harvest Control Rule**
Policy	**Zone Multipliers** **Reference Points**
Simulation Identification	**Run Description**

Entry fields grouped under the **Harvest Control Rule** field header allow one possible implementation of Canada's harvest strategy compliant with the Precautionary Approach (Figure 4, DFO 2006). Under this rule, harvest rates are progressively reduced from the maximum acceptable **Removal Rate** when the stock status falls below the **Upper Stock Reference** (USR) and are reduced to the lowest possible rate when the **Limit Reference Point** (LRP) is breached.

In the original documentation of Canada's harvest strategy (DFO 2006), the LRP and USR points are used to delineate three zones of stock status (Critical, Cautious, and Healthy; Figure 4). This constraint has been relaxed in *mseR* to allow flexibility when calculating performance measures based on these three zones (e.g., the number of years in which stock status was in the Cautious Zone). Two **Zone Multipliers**, a Limit Bound and an Upper Bound, are specified independently of the LRP and USR. For example, a management procedure could use a harvest control rule with a LRP of 0.4 of the biomass at maximum sustained yield, B_{MSY}, but establish a Lower Bound of $0.5B_{MSY}$ to delineate Critical and Cautious Zones (Figure 5). Thus, the estimated stock status level where the harvest control rule adjusts the perceived removal rate can be specified independently from the stock status zone boundaries.

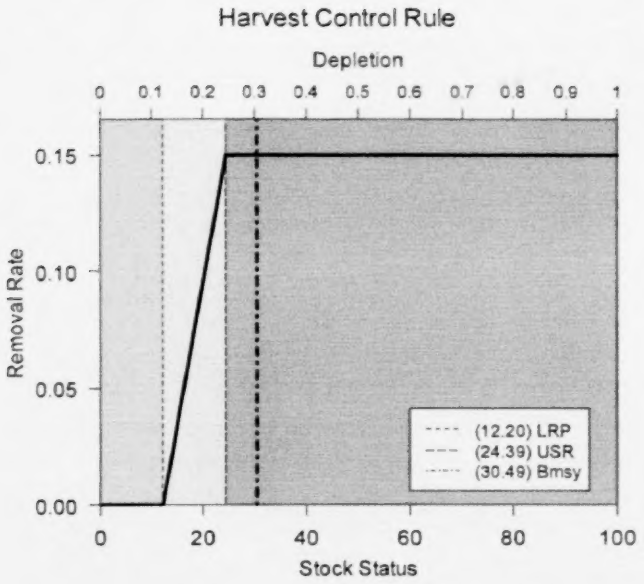

Figure 4. An example of the DFO (2006) harvest strategy where the LRP and USR values are set at multipliers of 0.4 and 0.8 of B_{MSY}, respectively, and the Lower and Upper bounds used to delineate stock status into Critical (pink), Cautious (yellow), and Healthy (green) zones are aligned with the LRP and USR. The removal rate over the range of stock status is indicated by the solid black line.

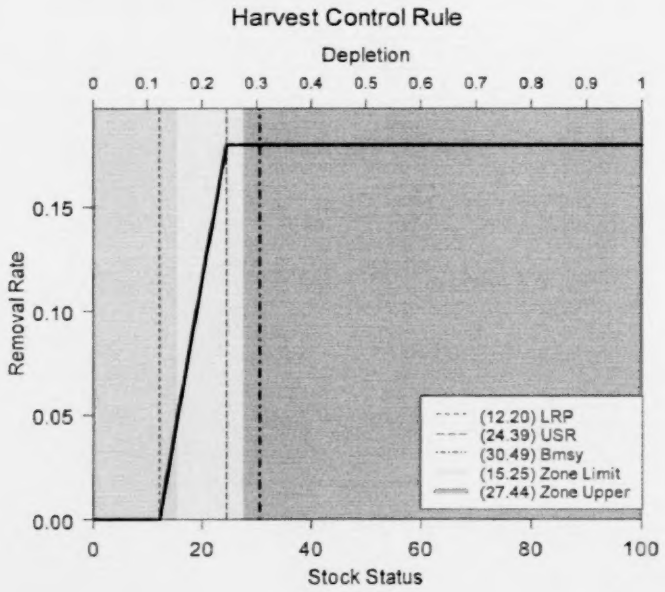

Figure 5. An example of the DFO (2006) harvest strategy where the LRP and USR used in the harvest strategy differ from the Lower and Upper zone bounds used to delineate stock status into Critical, Cautious, and Healthy zones. See caption for Figure 4.

Table 3. Selected field headings and entry fields for the *guiSim* control.

Field Header	Entry Field Name	Purpose
Survey Parameters	Survey sampling error	The survey sampling error obtained by one survey observation. For example, if set to a value of 2.2, one would require 2.2^2=4.84 repeated samples of the same station to achieve a coefficient of variation of 1. When set to 0, deterministic behaviour in the Old and New surveys is produced. A more detailed explanation of this field is provided in the text.
Scenario Conditions	Initial depletion target	The fraction of the unfished stock remaining in the first year of the procedure (t=tMP). Fishing mortality in years t=1,…, tMP-1 is adjusted for each replicate to produce a stock at approximately the specified initial depletion by year t=tMP.
Run Description	Scenario label	A (short) character string that describes the scenario (no spaces). The combination of Scenario label and Procedure label must be unique.
	Procedure label	A (short) character string that describes the procedure (no spaces). The combination of Scenario label and Procedure label must be unique.
Survey Data	Start Time	Year that Old or New survey starts, the Old survey ends in the year prior to the start of the New survey.
	Frequency	Frequency of Old or New, i.e., setting frequency to 3 produces a survey observation every third year starting in the survey year specified by Start Time.
	Stations	The number of survey stations in the Old or New survey used to control the relative difference in survey CV values.
Harvest Control Rule	Limit Reference Multiplier	Multiplier of B_{MSY} used for Limit Reference Point in the rule.
	Upper Reference Multiplier	Multiplier of B_{MSY} used for Upper Stock Reference in the rule.
	Removal Reference	F, instantaneous fishing mortality.
	Lambda 1	Fraction of previous year's catch applied to current year TAC.
Zone Multiplier	Limit Bound	Multiplier of B_{MSY} used for Limit Bound between Critical and Cautious zones.
	Upper Bound	Multiplier of B_{MSY} used for Upper Bound between Cautious and Healthy zones.

Table 4. *guiSim* control GUI buttons and their side effects.

***guiSim* Button**	**Side effect**
<Update>	• Checks all GUI fields for valid entries • Updates fishery reference points • Updates the graphics window
<Run>	• Checks all GUI fields for valid entries • Updates fishery reference points • Checks if scenario, procedure and run descriptions can be added to the simulation tracking file • Closes *guiSim* and all graphics windows • Runs the closed-loop feedback simulation
<Load>	• Loads a previously saved *mseR* parameter file
<Save>	• Saves the current GUI settings to a *mseR* parameter file
<Restart>	• Copies the current simulation tracking file to a backup file (previous backup files are overwritten) • Deletes the current simulation tracking file so that a new file can be started when <Run> is selected
<Exit>	• Exits the *guiSim* control GUI

The survey sampling error field located under the **Survey Parameters** header controls the partitioning of sampling variation between within-station and among-station components, thereby representing the spatial distribution of a population. Low values give the most weight to among-station components, which represents highly aggregated populations. Conversely, high values give most weight to within-station components and represent uniformly distributed populations. Increasing the number of stations sampled under the **Survey Data** header will be more beneficial when survey sampling error is low because a larger portion of total variation will be among-stations, which is the component of variation where additional sampling effort is directed.

There are currently two choices of **Assessment Method**. The Kalman Filter (KF), which requires a "gain" parameter KF Gain to be specified, and a Moving Average (MA). The latter method requires the user to specify the number of points in the moving average window. For example, if the value of Points to Average is set to 3, then the previous 3 survey points are averaged to estimate spawning stock biomass.

5.3 *mseR* VIEWER CONTROL GUI (*guiView*)

The ***mseR* Viewer Control** GUI, or *guiView*, allows the results of individual replicates within a simulation run to be inspected (Figure 6). The contents of the simulation tracking file are displayed in the pink fields at the top of the GUI. These fields are read-only and should not be edited in the GUI. Functioning of *guiView* is controlled via a set of radio buttons to select the type of plot displayed in an R graphics window, a set of check-boxes (Table 5), two entry fields, and six buttons (Table 6).

The radio buttons grouped under the **Plots** heading allow the selection of the type of plot displayed in an R graphics window. Only one plot may be selected at a time, and each plot applies only to the simulation specified by the **Simulation ID** number and **Replicate ID** number shown in the entry fields. The **Simulation ID** and **Replicate ID** entry fields allow a specific simulation number (located at the left hand side of the simulation list) or replicate number to be selected without using the <Previous> and <Next> buttons. Simply input the desired simulation and/or replicate number and press the keyboard <Enter> key to update the current plot.

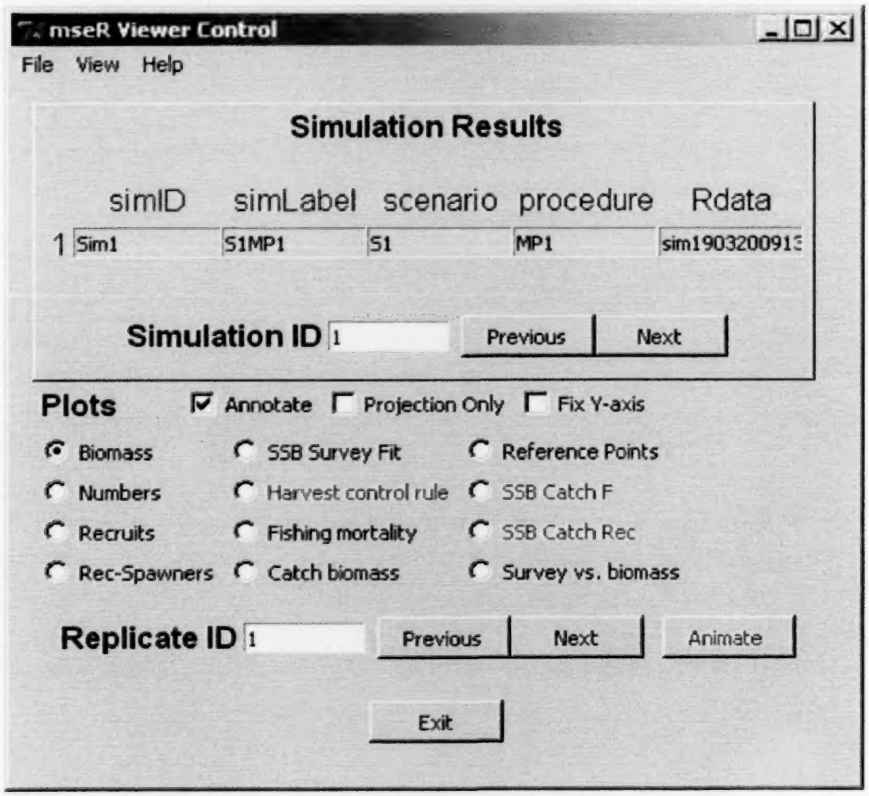

Figure 6. The *mseR* Viewer Control GUI.

All plots that display time trajectories generally have the first year of the procedure indicated by a dotted vertical line at t=tMP. The Reference Points plot from *guiSim* is repeated in *guiView* for convenience. Two plots, Survey vs. biomass and Harvest Control Rule do not display time series directly. The Survey vs. biomass plot displays the observed survey values against the spawning stock biomass. In the absence of statistical survey error, and if there is no bias, then the points should fall on a line of slope 1 since survey catchability is assumed to be 1.

Table 5. *guiView* control check-boxes and their side effects.

***guiView* Checkbox**	**Side effect**
Annotate	• Select to display titles, legends and other annotation on plots
Projection Only	• Select to display ONLY the projection period along the X-axis from year tMP to nT
Fix Y-axis	• Select to fix the Y-axis on plots to the same scale • Note that some points may be out of range and not displayed, and for some plots there is a side effect on the X-axis

Table 6. *guiView* control buttons and their side effects.

***guiView* Button**	**Side effect**
<Previous> *Simulation results*	• Decrements the **Simulation ID** number by one • Updates the graphics window
<Next> *Simulation results*	• Increments the **Simulation ID** number by one • Updates the graphics window
<Previous> *Simulation result*	• Decrements the **Replicate ID** number by one • Updates the graphics window
<Next> *Simulation results*	• Increments the **Replicate ID** number by one • Updates the graphics window
<Animate>	• Animates the plot in time steps, then pauses for 3 seconds before returning to the static plots • Applies only to plots labelled with blue text, e.g., SSB Catch F, SSB Catch R and Harvest Control Rule plots
<Exit>	• Exits the *guiView* control GUI

The Harvest Control Rule plot (Figure 7) displays the realized fishing mortality against spawning stock biomass super-imposed on the harvest control rule and stock status zones (i.e., Critical, Cautious, Healthy zones) *for the projection period only*. The colour of the points indicates time progression by the use of increasingly "hotter" colours over time, i.e., white colours indicate points close to the first year of the procedure (tMP) and red points indicate points closer to the end of the simulation (nT). This plot can be animated using the <Animate> button, as can the SSB Catch F and SSB Catch R plots.

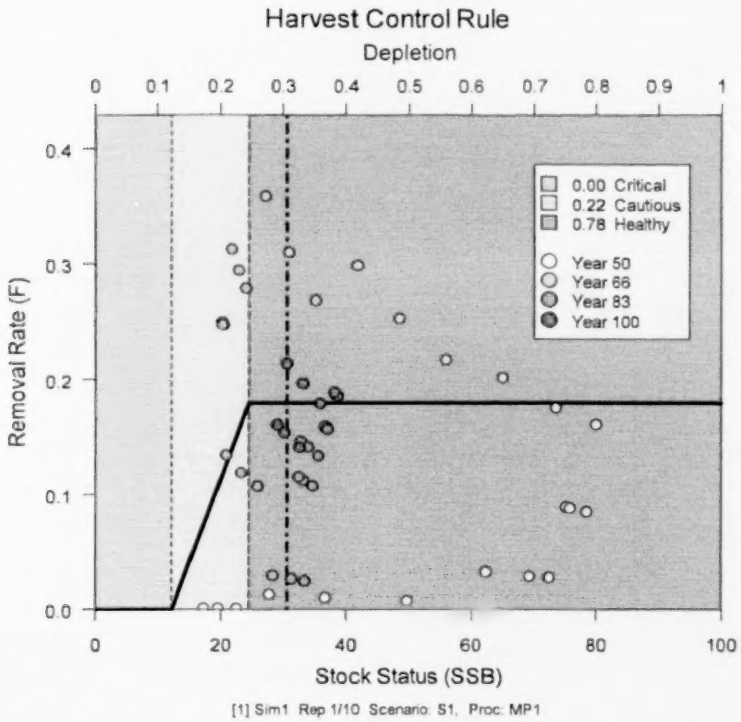

Figure 7. The Harvest Control Rule plot produced by *guiView*. The legend indicates the proportion of projection years that the spawning stock biomass fell into each of the Critical, Cautious and Healthy zones (pink, yellow and green circles). The legend labels "Year xx" indicate the "cold to hot" colour gradation over time for the projection years.

5.4 *mseR* PERFORMANCE STATISTICS CONTROL GUI (*guiPerf*)

The relative performance of candidate management procedures specified for each simulation scenario can be evaluated by comparing statistics related to fishery objectives. The ***mseR* Performance Statistics Control**, or *guiPerf*, is used to select and view the following types of plots (Figure 8):

1. Simulation envelopes that summarize quantiles of the distribution of depletion, catch, and fishing mortality;
2. Barplots that contrast the expected depletion, catch, and volatility performance over pre-specified time periods;
3. Plots of depletion and fishing mortality performance against fishery objectives.

In addition, *guiPerf* produces tables of performance statistics and outputs the information to Microsoft Excel for inspection or subsequent plotting by the user.

The contents of the simulation tracking file are displayed in the pink fields at the top of the GUI, where the first year of the procedure (tMP), number of years in the simulation (nT), and number of replicates (nReps) are shown along with information that identifies each simulation. These fields are read-only and should not be edited within the GUI. However, a suite of entry fields appear under the tracking information that control the time periods over which performance statistics are calculated, calculations related to objectives, and the ranges of various plot axes (Table 7). Checkboxes located to the right of the tracking information under the Select heading are used to determine which simulations appear in plots produced by the GUI. Other check-box functions are listed in Table 8. Control buttons are listed in Table 9.

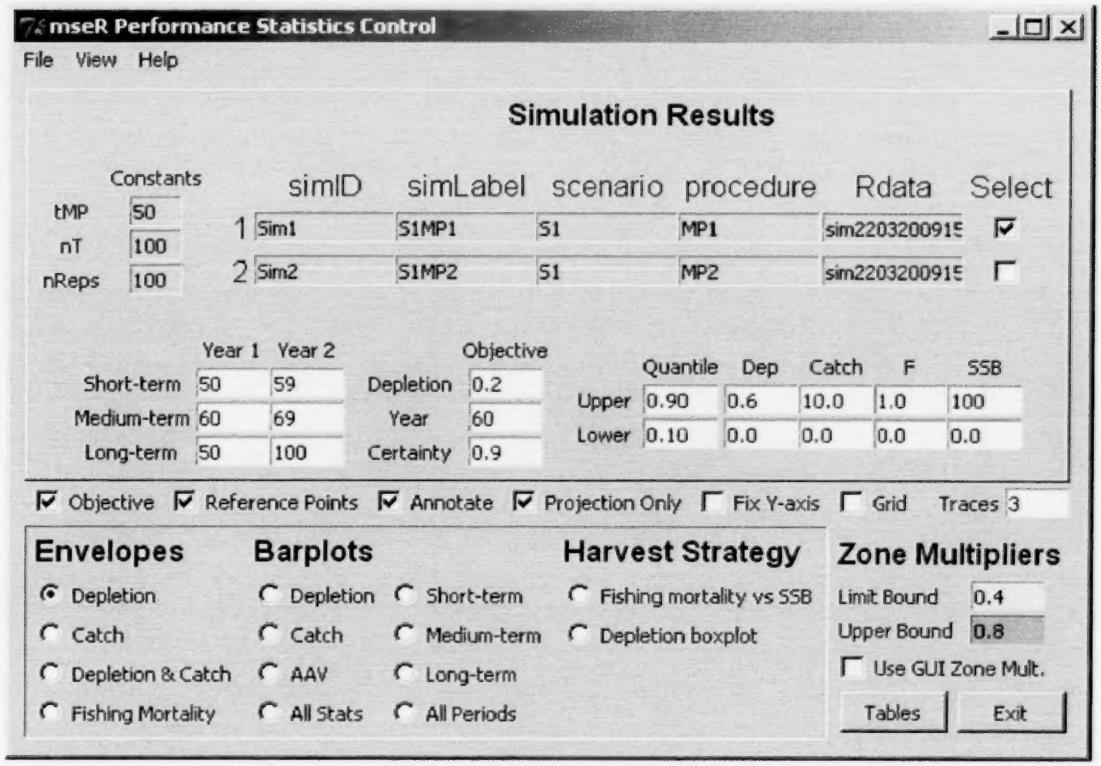

Figure 8. The *mseR* Performance Statistics Control GUI.

Performance statistics shown in plots or produced as tabular output are generally quantiles of the distribution of statistics computed for each replicate. For example, the median average catch is the median of average catch values calculated for each replicate *over a specified time period.* For example, suppose there are 100 replicates, and the statistics are requested over the period from 50 to 59 years. An average for each replicate is computed from the 10 catch values produced for years 50,…, 59. Then, the median of the 100 averages resulting from each replicate is computed. A similar computation is performed for other quantiles of catch, or any other variable, such as the 10^{th} or 90^{th} percentiles. The *guiPerf* control can produce **Barplots** that summarize the distributions of spawning biomass depletion, catch and catch variability over the specified time

periods. Variability in catch (e.g., catch volatility) is characterized by the average annual variation (AAV) in catch from one year to the next expressed as a proportion of the average annual catch. This performance statistic is often used to measure the attainment of an objective related to minimizing catch variability.

Table 7. *guiPerf* control entry fields.

***guiPerf* Entry Field**	**Description**
Short-term Medium-term Long-term	• The entries under the columns Year 1 and Year 2 indicate the years that delimit the time periods of each summary period • The value for Year 1 must be less than Year 2 and both must be greater than or equal to tMP • There is, in fact, no restriction that Short-term must be less than Long-term in period length or start time, etc.
Objective Depletion Year Certainty	• A series of performance statistics are calculated that hold two of the three values of Depletion, Year, and Certainty fixed in turn. These types of performance statistics are called 'objective outcomes' and can be displayed on the envelope plots produced by *guiPerf* • For fixed Year and Certainty, the calculated objective outcome is that depletion value at time Year where the probability of exceeding the value is Certainty (`depAtYearProb` in Excel output) and is shown as C:0.xx on an envelope plot, e.g., C:0.25 • For fixed Depletion and Certainty, the calculated objective outcome is the first year after tMP when the probability that the depletion is greater than or equal to the specified Depletion is Certainty (`yearAtDepProb` in Excel output) and is shown as Y:xx on an envelope plot, e.g., Y:62 • For fixed Depletion and Year, the calculated objective outcome is the proportion of depletion values at Year greater than or equal to Depletion (`progAtDepYear` in Excel output) and is shown as D:0.xxx on an envelope plot, e.g., D:0.021
Upper Lower Quantile Dep Catch F SSB	• Upper and lower limits for Quantiles shown on plots, where relevant (e.g., simulations envelopes, barplots) • Axis limits for depletion (Dep), catch (Catch), fishing mortality (F) and spawning stock biomass (SSB) • The side effect of the Dep, Catch, F and SSB entry fields is to fix the axis limits to the specified range for all plots appearing in a graphics window ***when the*** Fix Y-axis ***box is checked***
Traces	• The number of random traces of individual replicate time trajectories to show on simulation envelope plots • If Traces is 0, then traces are not shown
Limit Bound	• Multiplier of B_{MSY} used for the Critical-Cautious zone limit bound
Upper Bound	• Multiplier of B_{MSY} used for the Cautious-Healthy zone upper bound

Table 8. *guiPerf* control check-boxes and their side effects.

***guiPerf* Checkbox**	**Side effect**
Select	• Check one or more boxes to display the results for the corresponding simulation
Objective	• Check to display the Objective outcomes on plots, if applicable
Reference Points	• Check to display relevant fishery reference points on plots
Annotate	• Check to display legends and relevant annotation on plots
Projection Only	• Check to display ONLY the projection period from tMP to nT
Fix Y-axis	• Check to fix the Y-axis on multiple panel plots to the same scale, sometimes there is a side effect on the X-axis
Grid	• Display a blue cross-grid in the background to assist judging differences between plots
Use GUI Zone Mult.	• Check to over-ride the zone multipliers stored with the simulations by *guiSim*

Table 9. *guiPerf* control buttons and their side effects.

***guiPerf* Button**	**Side effect**
<Tables>	• Checks all GUI fields for valid entries • Updates fishery reference points • Calculate performance statistics for all simulations in the simulation tracking file, regardless of whether they are selected in the GUI • Outputs tables of results to Microsoft Excel and opens the Excel file for viewing
<Exit>	• Exits the *guiPerf* control GUI

Simulation **Envelopes**, also called tulip or worm plots (Rademeyer et al. 2007), summarize the distribution of the possible realizations of projection outputs. For example, the distributions of catch or spawning biomass depletion could be summarized over the simulation replicates for a given management procedure. In *mseR*, simulation envelopes are comprised of a shaded region bounded by the 5^{th} and 95^{th} percentiles of the distribution at each time step. The user can specify trajectories of statistics corresponding to two other quantiles such as the 10^{th} and 90^{th} percentiles which are shown using red lines. The median statistics always appears as a thick solid black line. The Traces entry field allows individual replicate trajectories to be superimposed on the envelope.

The objective outcomes described in Table 7 can be displayed on the simulation envelopes when the "Objective" control is checked. These outcomes are a series of performance statistics that show the value of one of Depletion, Year, or Certainty subject to the remaining two values being fixed at the values shown on the GUI. These specific calculations ignore the short, medium, and long-term time limits and are calculated over the entire projection period from tMP to nT. For example, Y is the first year after tMP for which the Certainty that the Depletion is greater than or equal to the specified Depletion is

Certainty, (b) D is the depletion value at time Year for which the probability of exceeding the value is equal to the specified level of Certainty, and (c) C is the proportion of depletion values at Year greater than or equal to Depletion.

Two plots are currently available under the **Harvest Strategy** header. The Fishing Mortality versus SSB plot shows the realized instantaneous fishing mortality, F_t, in each year of the projection period plotted against the spawning stock biomass, B_t, for every replicate (Figure 9). The small white circles represent the set $\{F_{tj}, B_{tj}\}$ for t=tMP,…,nT and j=1,…,nReps. These points are superimposed on the stock status zones (Critical, Cautious, Healthy) and the harvest control rule is overlaid as a thick solid line. The point $\{F_{MSY}, B_{MSY}\}$ is represents a "target" and is shown as a large white circle.

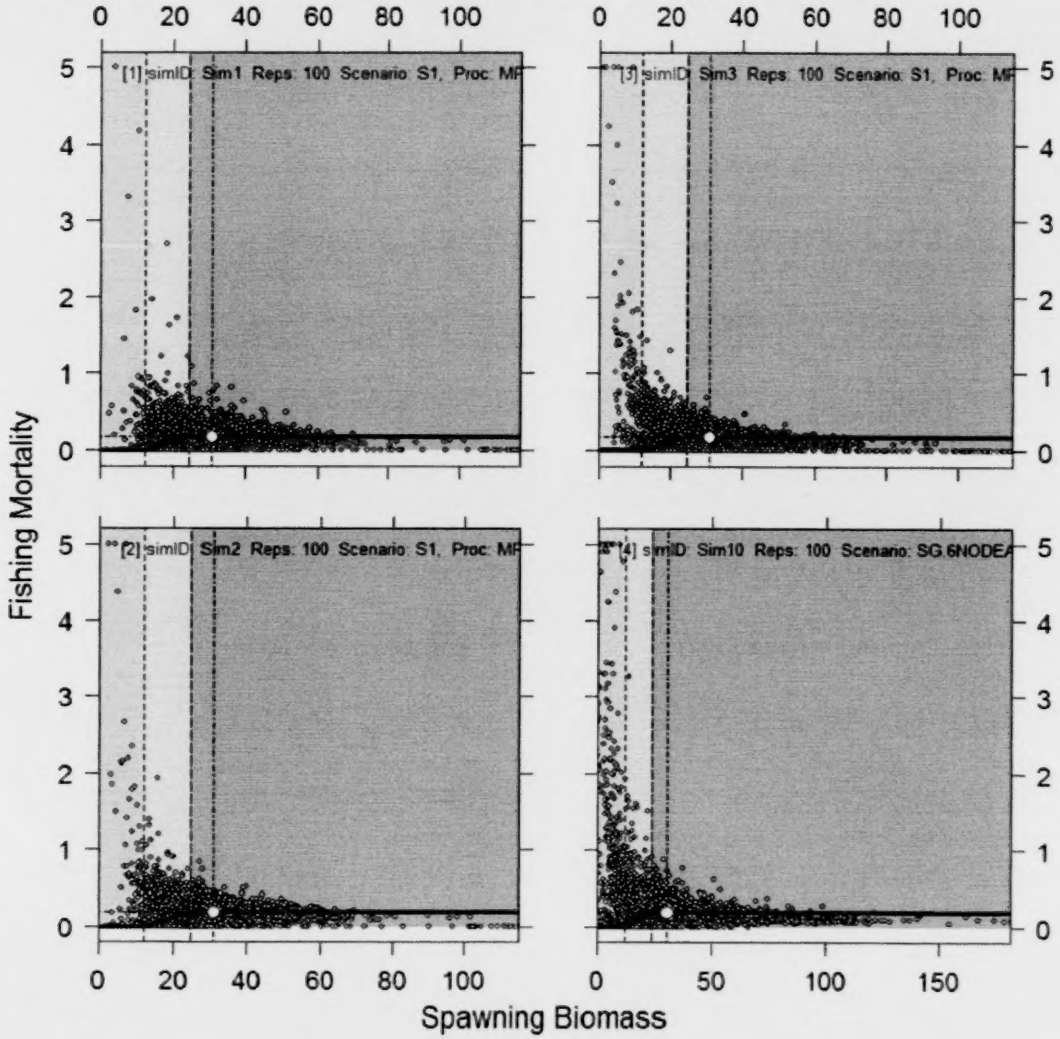
Fishing Mortality
Spawning Biomass
[1] simID: Sim1 Reps: 100 Scenario: S1, Proc: MF
[2] simID: Sim2 Reps: 100 Scenario: S1, Proc: MF
[3] simID: Sim3 Reps: 100 Scenario: S1, Proc: MF
[4] simID: Sim10 Reps: 100 Scenario: SG.6NODE

Figure 9. The Fishing Mortality versus SSB plot. The Critical, Cautious and Healthy zones are indicated by the pink, yellow and green regions, respectively. Small white circles show the realized fishing mortality against spawning stock biomass for each

projection year for all replicates. The large white circle represents $\{F_{MSY}, B_{MSY}\}$, while the solid line shows the combinations of $\{F, B\}$ prescribed by the harvest control rule.

The Depletion boxplots plot is shown in Figure 10. The Critical, Cautious and Healthy zones are indicated by the pink, yellow and green coloured regions, respectively. Each figure panel represents a user-specified time horizon, e.g., Short, Medium and Long where the numbers in the panel label indicate the year range of the summary period. Each boxplot summarizes the replicate values of average depletion for one simulation. For each simulation shown, the small white circles show the average spawning stock depletion for each replicate over the period indicated. The lower and upper limits of the box represent user-specified quantiles, typically the 10^{th} and 90^{th} percentiles of the distribution of average spawning stock depletion. The thick horizontal line is the median value of average spawning stock depletion. The red circle represents the spawning stock depletion at MSY, D_{MSY}, which can be considered a "target" – if the white circles are largely in the Healthy zone and tightly clustered around D_{MSY}, then the management procedure could be judged to have relatively good performance.

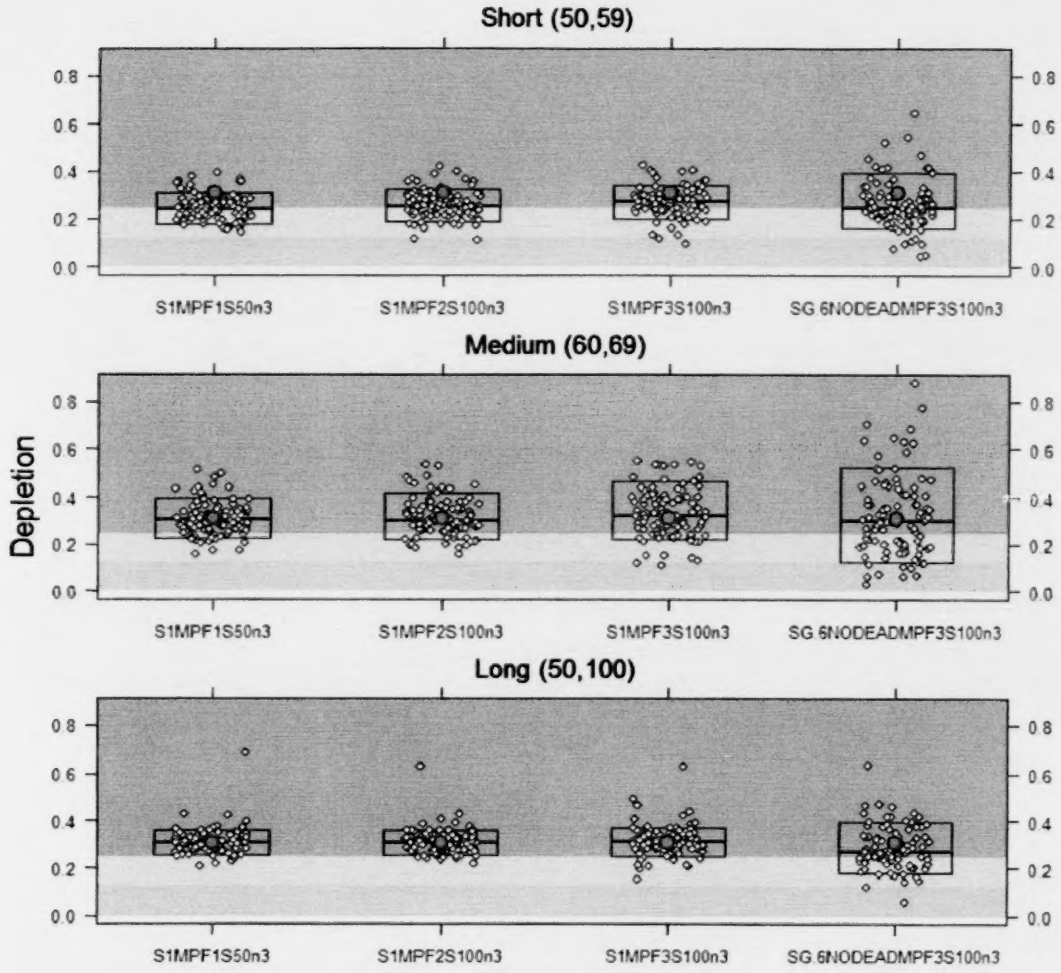

Figure 10. The **Depletion boxplots** plot. The Critical, Cautious and Healthy zones are indicated by the pink, yellow and green coloured regions, respectively. For each simulation shown, the small white circles show the average spawning stock depletion for each replicate over the period indicated. The lower and upper limits of the box represent user-specified quantiles, typically the 10^{th} and 90^{th} percentiles of the distribution of average spawning stock depletion. The thick horizontal line is the median value of average spawning stock depletion. Red circles indicate the depletion at MSY, D_{MSY}.

6 MANAGING SIMULATION RESULTS: *mseRsimTracker.txt*

Simulations are linked by a tracking file called *mseRsimTracker.txt*. The tracking file is a comma-delimited text file where the first line is a comment field and the second line contains field headers. The fields are listed in Table 10.

Table 10. Simulation tracking file field names, types and description.

Field Name	Field Type	Description
simID	Character	Unique label assigned by *mseR*
simLabel	Character	Join of scenario and procedure, must be unique
scenario	Character	Label for scenario (no spaces)
procedure	Character	Label for procedure (no spaces)
Rdata	Character file name	Name of *Rdata* file containing simulation results
Select	Boolean (True/False)	If true, the simulation will be plotted
tMP	Integer	Start year of management procedure
nT	Integer	Last year of simulation (nT > tMP)
nReps	Integer	Number of simulation replicates

Each time the <Run> button in *guiSim* is pressed, the current simulation settings are checked for valid entries and against the contents of the current tracking file, if it exists. The rules for a valid tracking file are listed below:

- The **simID** values must be unique, cannot contain spaces but alpha-numeric strings are permitted – usually the **simID** is assigned by *mseR*;
- The **simLabel** values must be unique and cannot contain spaces – by default these labels are constructed by concatenating the **scenario** and **procedure** fields;
- The **scenario** label cannot contain spaces but alpha-numeric strings are permitted;
- The **procedure** label cannot contain spaces but alpha-numeric strings are permitted;
- The **Rdata** file name assigned by *mseR*;
- At least one simulation must be "checked" using the **Select** check box – if none are selected then *mseR* enforces selection of the first simulation in the list;
- **tMP** is the first year of the procedure and must be the same for all file entries;
- **nT** is the last year of the simulation and must be the same for all tracking file entries;
- **nReps** is the number of replicates and must be the same for all tracking file entries.

If the simulation can be added to the current tracking file, then *mseR* calls the function `runMSE` to start the feedback loop. Upon completion of the loop the new tracking information is written to *mseRsimTracker.txt* and the simulation results are written to a new **.Rdata* file. The name of the **.Rdata* file is determined by the current day, month, year, hour, minute and second as determined from the system clock, i.e., *sim26022009115707.Rdata* was written on February 26, 2009 at 11:57:07 in the morning.

7 SAVING A RECORD OF THE SIMULATIONS: *mseRStatistics.xls*

One of the functions of the *guiPerf* control is to save a complete record of the simulations linked by an *mseRsimTracker.txt* tracking file. The <Tables> button utilizes the *RODBC* package to write simulation parameter settings and results to Microsoft Excel into five worksheets named "Tracking", "Sim_Parameters", "Perf_Parameters", "Sim_Summary1", and "Sim_Summary2". The contents of each worksheet are described in the following list:

- **Tracking**: The contents of the simulation tracking file, *mseRsimTracker.txt*;
- **Sim_Parameters**: The *guiSim* control parameters for each simulation listed in the tracking file. The worksheet rows are the parameter names and parameter values for each simulation occur in successive columns under each **simID** label;
- **Perf_Parameters**: The *guiPerf* control parameters specified at the time the Excel table was created;
- **Sim_Summary1**: Performance statistics (Table 11) for each simulation arranged in a "spreadsheet" view with identifying labels for the simulation and time period over which the statistics were computed;
- **Sim_Summary2**: Performance statistics for each simulation arranged in a "normalized" view for plotting or database storage. This worksheet contains the same information stored in the "Sim_Summary1" worksheet.

Note that these Excel spreadsheet files must be opened manually when using a Mac OS platform. Excel files open automatically when using a Microsoft Windows OS.

Table 11. Performance statistics produced by the <Tables> button of the *guiPerf* control.

Statistic Name	Description
medAvgDep	Median of average depletion values over replicates
Q1AvgDep	Quantile 1 of average depletion values over replicates (user-specified)
Q2AvgDep	Quantile 2 of average depletion values over replicates (user-specified)
medFinalDep	Median depletion over replicates at the end of the time period
Q1finalDep	Quantile 1 of the depletion over replicates at the end of the time period
Q2finalDep	Quantile 2 of the depletion over replicates at the end of the time period
medLowDep	Median of the minimum depletion values over replicates
Q1lowDep	Quantile 1 of the minimum depletion values over replicates
Q2lowDep	Quantile 2 of the minimum depletion values over replicates
medAAV	Median of annual average variation (AAV) in catch over replicates
Q1AAV	Quantile 1 of AAV values over replicates (user-specified)
Q2AAV	Quantile 2 of AAV values over replicates (user-specified)
medAvgCatch	Median over average catch values over replicates
Q1AvgCatch	Quantile 1 of average catch values over replicates (user-specified)
Q2AvgCatch	Quantile 2 of average catch values over replicates (user-specified)
criticalP	The proportion of time in the Critical Zone over replicates
cautiousP	The proportion of time in the Cautious Zone over replicates
healthyP	The proportion of time in the Healthy Zone over replicates
yearAtDepProb	Year where depletion reaches or exceeds the user-specified level with the user-specified probability
probAtDepYear	Probability of reaching or exceeding the user-specified depletion at the user-specified year
depAtYearProb	Depletion at the user-specified year and user-specified probability of reaching or exceeding the depletion.
probGteDmsy	Proportion of time that the SSB depletion is greater than or equal to depletion at MSY, D_{MSY} (i.e., B_{MSY}) over replicates
probGteLimit	Proportion of time that the SSB depletion is greater than or equal to the depletion at the limit reference point.

8 THE CLOSED-LOOP FEEDBACK FUNCTION: `runMSE`

Users who modify the *mseR* operating model code should run *mseR* directly from the command line using the `runMSE()` function. This will invoke the feedback loop directly from the R command-line console without mediation by the *guiSim* control GUI. All that is required is that the R working directory contains a valid *inputParameters.par* file and an *mseRsimTracker.txt* file compatible with the settings specified in *inputParameters.par*. That is, the *inputParameters.par* file must specify the same values for **nT**, **tMP**, and **nReps** already stored in the tracking file and cannot contain a duplicated **simLabel** value, usually derived from the **scenario** and **procedure** labels.

Alternately, the *mseRsimTracker.txt* file can be renamed or deleted and a new collection of simulations compiled. To run a feedback loop simply enter the command `runMSE()` at the R command-line console. Interested users can inspect the *mseRsim_funs.r* source file and use the flow chart shown in Figure 11 as a guide to the R functions required to implement the feedback loop.

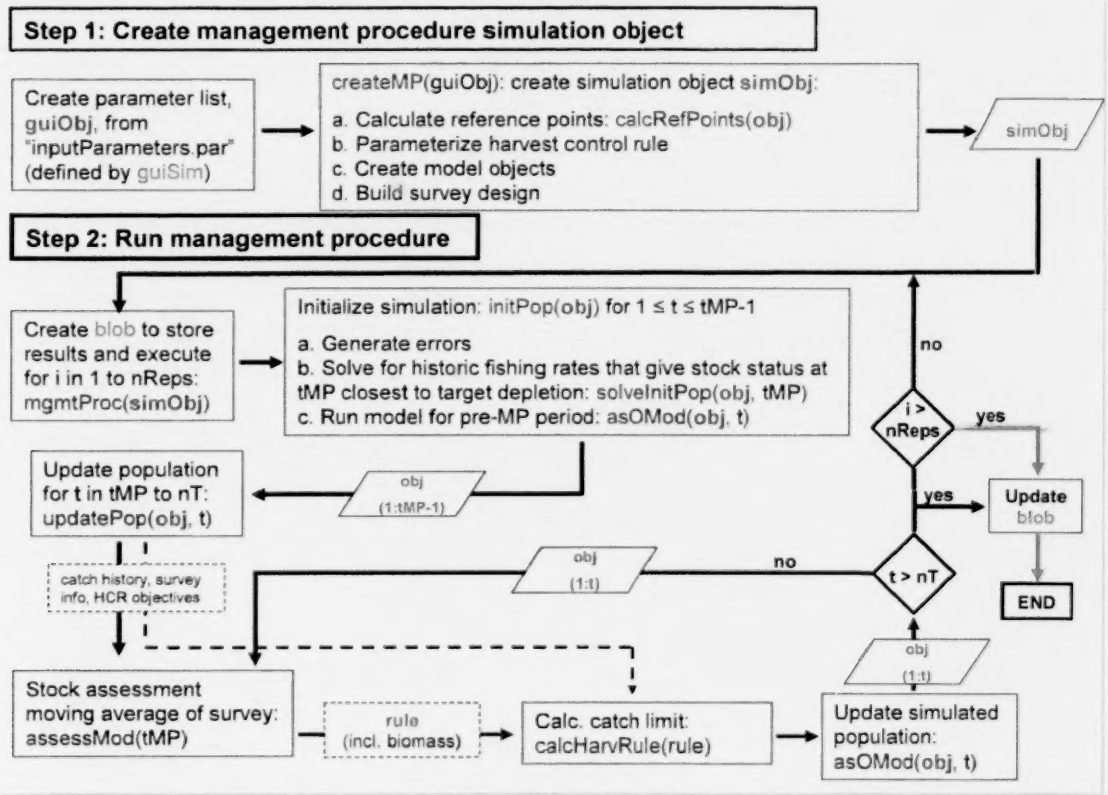
Step 1: Create management procedure simulation object
Create parameter list, guiObj, from "inputParameters.par" (defined by guiSim)
createMP(guiObj): create simulation object simObj:
a. Calculate reference points: calcRefPoints(obj)
b. Parameterize harvest control rule
c. Create model objects
d. Build survey design
simObj
Step 2: Run management procedure
Create blob to store results and execute for i in 1 to nReps: mgmtProc(simObj)
Initialize simulation: initPop(obj) for 1 ≤ t ≤ tMP-1
a. Generate errors
b. Solve for historic fishing rates that give stock status at tMP closest to target depletion: solveInitPop(obj, tMP)
c. Run model for pre-MP period: asOMod(obj, t)
no
i > nReps
yes
Update blob
yes
Update population for t in tMP to nT: updatePop(obj, t)
obj (1:tMP-1)
catch history, survey info, HCR objectives
obj (1:t)
no
t > nT
END
obj (1:t)
Stock assessment moving average of survey: assessMod(tMP)
rule (incl. biomass)
Calc. catch limit: calcHarvRule(rule)
Update simulated population: asOMod(obj, t)

Figure 11. Flowchart of steps required to implement the `runMSE` function feedback loop.

8.1 INPUT PARAMETERS FILE: *INPUTPARAMETERS.PAR*

The *guiSim* control writes a file called *inputParameters.par* that is used by the feedback loop function, `runMSE`. This file is a space-delimited text file that can be edited directly, although it is recommended that the *guiSim* control be used as validation checking is enforced for parameter values and compatibility with the existing simulation tracking file. An example is shown as Table 12. Note that first line is a comment line containing the date and time the file was written and the second line contains the headers **parameter** and **value**. Each **parameter** entry is a character string that contains dollars signs "`$`" that determine the internal storage structure of the parameters when they are passed to the `runMSE` function. Note that when the **value** entry is a character string, the character string must appear in double quotes.

Table 12. Example *inputParameters.par* file.

```
# mseRsimGui GUI parameters written Thu Feb 26 11:54:58 2009
parameter value
pars$B0 100
pars$rSteepness 0.75
pars$gammaR 0
pars$sigmaR 0.7
pars$aMat50 6
pars$aMat95 9
pars$aSel50 6
pars$aSel95 9
pars$M 0.15
pars$c1 1e-06
pars$c2 3
pars$Linf 80
pars$L1 20
pars$vonK 0.2
pars$sigmaL 0.4
pars$qSurvey 1
pars$tau 0.5
pars$nT 100
pars$tMP 50
pars$nAges 25
pars$initDepTarg 0.15
pars$nReps 100
pars$rseed 1234
other$scenarioLabel "S1"
other$mpLabel "MP2"
mp$data$t1Survey 20
mp$data$t2Survey 52
mp$data$k1Survey 1
mp$data$k2Survey 3
mp$data$nStations1 100
mp$data$nStations2 100
mp$assess$assessMethod "movinAvg"
mp$hcr$limitRefMult 0.4
mp$hcr$upperRefMult 0.8
mp$hcr$remRate 0.1918
mp$hcr$lam1 0
mp$assess$avgPoints 1
other$limitBoundMult 0.4
other$upperBoundMult 0.8
other$ssbFmsy 29.0801
other$yieldFmsy 5.3038
other$Fmsy 0.218
other$F0 0
other$F01 0.1918
other$F40 0.1778
other$Fmax 0.5696
other$Fcra 1.1907
other$simPlotType "hcr"
```

8.2 OUTPUT FILES: *SIMDDMMYYHHMMSS.RDATA*

As noted in the section describing the *guiPerf* control, each simulation is saved in a separate **Rdata** file. The file name is determined by the current day (*DD*), month (*MM*), year (*YY*), hour (*hh*), minute (*mm*) and second (*ss*) as determined from the system

clock. For example, the simulation results file *sim26022009115707.Rdata* was written on February 26, 2009 at 11:57:07 in the morning.

The results of each simulation are stored as an R "list" object within the *simDDMMYYhhmmss.Rdata* file. An R list is an object comprised of an ordered collection of other objects known as list "components". The components do not need to be of the same type, for example, a list could contain a numeric vector, a matrix, a character array, a function and a data frame (itself a type of list). Each list component is numbered and may be referred to using its number. For example, if `myList` is the name of a list with four components then each may be individually referenced as `myList[[1]]`, `myList[[2]]`, `myList[[3]]` and `myList[[4]]`. Suppose further that the fourth list component is a vector. The third element of the vector could be referenced directly using `myList[[4]][3]`.

List components may also be named. For example, a list can be built by entering the following statement at the R command console:

```
myList<-list(pars=c(0,80.0,0.1),om=matrix(0.0,nrow=20,ncol=100))
```

The list `myList` would consist of a three element vector named "pars" and a 20 by 100 numeric matrix filled with values of 0.0 and named "om". The "pars" vector could be referenced using `myList[[1]]` or directly by name using `myList$pars`, or alternatively using `myList[["pars"]]`.

Simulation results for *mseR* are stored as a very large R list object (Table 10). This list object structure changes frequently with *mseR* development as information is added or removed, and thus behaves like an amorphous "blob". Indeed, when the results of a simulation are loaded by a *mseR* control, they appear in the R working directory as a list object called `blob`, which also has the benefit of being a short variable name. The `blob` is currently organized into four named components: `pars`, `om`, `mp`, and `simGuiPars`. The `simGuiPars` component is itself a list derived from the *inputParameters.par* file and can be ignored by the user. The `pars` component is a long, named list of scalar parameters written by the *guiSim* control that is combined with vectors that result from calculating fishery reference points. To view the contents of the `par` component enter the R command `blob$pars` or get a list of names by entering `names(blob$pars)`.

Operating model variables are stored in the `om` component, while variables associated with the management procedure are stored in the `mp` component. The latter is organized into `data`, `assess`, and `hcr` components. The names of components nested within `om` can be determined by entering `names(blob$om)` at the R command console. For example, one of the components of `blob$om` is called `Bt`, which is a matrix that holds the spawning stock biomass estimates for each time step and replicate. The spawning stock biomass component of `om` can be referenced directly by `blob$om$Bt`, and a specific element of the matrix can be reference using row and column indicators. For example, the spawning stock biomass corresponding to year 61 and replicate 48 of the simulation can be accessed using `blob$om$Bt[48,62]` or

`blob$om$Bt[48, "B61"]`. In the former case, the 62nd column of the matrix is specified because the first column of `Bt` is a vector named `iRep` that holds the replicate number. The entire time trajectory of spawning stock biomass values for replicate 48 can be referenced by entering `blob$om$Bt[48,]` while all the values obtained for spawning biomass in year t=61 of the simulation can be referenced either by `blob$om$Bt[,62]` or `blob$om$Bt[,"B61"]`. Most components of `blob` that have names ending with "`t`" are similarly referenced, where "`t`" indicates a time series.

Table 13. Structure of the R list object that holds the results for each simulation.

1st-Level	2nd-Level	3rd-Level	Description
`pars`	*Parameters* *Reference points*	*NA*	Selected *guiSim* parameters Vectors for plotting

`om`	`Bt`
	`Nt`
	`Btot`
	`Ntot`
	`Rt`
	`It`
	`Dt`
	`Ft`
	`surveyCV`
		NA	Spawning stock biomass at time t
			Spawning numbers at time t
			Total biomass at time t
			Total numbers at time t
			Recruitment numbers at time t
			Survey biomass at time t
			Catch biomass at time t
			Fishing mortality at time t
			Coefficient of variation of surveys

`mp`	`data`	`It`	Observed survey biomass at time t
	`assess`	`Bt`	Estimated spawning biomass at time t

	`hcr`	`limitRefMult`
		`upperRefMult`
		`remRate`
		`lam1`
		`tMP`
		`nT`
		`Bmsy`
		`Fmsy`
		`MSY`
		`limitRefPt`
		`upperStockRef`
			Limit reference point multiplier
			Upper stock reference multiplier
			Removal rate above `upperRefMult`
			Fraction of catch in year t-1 used in year t
			First year of management procedure
			Last year of simulation
			Spawning biomass at MSY
			Fishing mortality at MSY
			Maximum sustained yield
			Limit reference point (spawning biomass)
			Upper stock reference (spawning biomass)

`simGuiPars`	`pars,mp,other`	*various*	Derived from *inputParameters.par*

9 EXAMPLE EXERCISE

The goal of this exercise is to become familiar with the design, execution, and analysis of closed-loop fisheries simulations using the *mseR* software package. The exercise will proceed through a sequence of steps from fishery system conceptualization to the analysis of simulated performance. Users will:

1. Learn how to set-up a closed-loop fishery simulation using the *mseR* **Simulation Control** GUI, `guiSim();`

2. Verify the correct execution of individual simulation replicates using the *mseR* **Viewer Control** GUI, `guiView();`

3. Evaluate the relative performance of candidate management procedures against management objectives using the *mseR* **Performance Statistics Control** GUI, `guiPerf()`.

A common goal of survey design is to establish the relationship between the number of survey stations and the resulting level of precision of stock biomass estimates. The degree to which the survey can be optimized depends on resources and objectives. For example, because survey effort can be translated into total costs, one must decide which level of effort is optimal for a given level of resources. However, it cannot be claimed that the resulting survey precision is also optimal for managing the fishery because we have not determined the effect on our ability to meet management objectives. Such a determination requires a more in-depth analysis of feedbacks between the survey, the management system, and the fish population which is facilitated by closed-loop simulations as implemented in *mseR*.

This exercise deals with the management of a generic groundfish population that has been heavily fished in the past. The stock has an age-at-50% maturity (a_{50}) of 6 years and a natural mortality rate (M) of 0.15/yr. Selectivity to the fishery coincides with maturity because fish are also recruited to the fishery beginning at age-6. At the start of the management procedure in year $t = 50$, the spawning biomass is depleted to 15% of the unexploited spawning biomass. It has been proposed that the annual survey that occupies 50 stations be changed to a 150-station survey conducted every 3 years. This change in survey design is anticipated to reduce costs and allow the research vessel to be used for other purposes in years between surveys. The fishery team (i.e., fishery biologist and manager, possibly resource stakeholders) has identified 6 management objectives that are given Table 14. The team has several choices to make about their management procedure:

(1) First, they must determine whether changing from a 50-station survey every year (i.e., survey frequency of 1) to a 150-station survey every three years (i.e., survey frequency of 3) will worsen or improve the expected ability to meet management objectives.

(2) Second, because the survey is only one component of the overall management system, the form of the harvest control rule also needs to be considered. Selected DFO policy documents such as the web document "*A fishery decision-making framework incorporating the Precautionary Approach*" (DFO 2009) suggest Limit and Upper Stock reference points of LRP=$0.4B_{MSY}$ and USR=$0.8B_{MSY}$, respectively. The team will determine how these suggested reference points will affect their ability to meet catch objectives compared to their existing constant F strategy (i.e., LRP=$0.005B_{MSY}$, USR=$0.01B_{MSY}$). Both harvest strategies use a Removal Reference fishing mortality rate equal to F_{MSY}.

Table 14. Management objectives for the *mseR* exercise.

Type	Management Objective	Time period
Conservation	a. Reach a target stock size of B_{MSY} with 90% certainty.	Year 63
	b. Maintain "Healthy" stock size of at least B_{MSY} in 50% of years.	50 -100
	c. Avoid "Critical" stock sizes less than $0.5B_{MSY}$ with 95% certainty in each year.	50 -100
Catch variability	d. Limit changes in catch to less than 20% per year.	50 -100
Yield	e. Maintain minimum stable catch of at least 30% of MSY.	50 - 100
	f. Maximize average annual yield	50 - 100

Four simulation runs are needed to determine those two choices. The same scenario about population and life history parameters will be used for all simulations; but four different management procedures will be considered. These four procedures are MP1: 50-station survey every year with the new harvest strategy, MP2: 150-station survey every 3 years with the new harvest strategy, MP3: 50-station survey every year with a constant F strategy, and MP4: 150-station survey every 3 years with a constant F strategy.

To help inform the decisions described above, follow these steps using *mseR*:

(1) At the R console, enter the command `guiSim()` to launch the ***mseR* Simulation Control** GUI and press the <Restart> button. This button will delete the existing *mseRsimTracker.txt* file.

(2) Configure the *mseR* Simulation Control GUI to look the same as that shown in Figure 12. Note that the fields under **Survey Data** label should be specified as two time periods with the same frequency and number of stations to simulate a management procedure in which the existing 50-station survey is continued for the entire 100 year period. Also note that the fields under the **Harvest Control Rule** label are set to the new harvest strategy.

(3) Press <Update> to view a figure of the harvest control rule just specified. Figures of life history schedules and reference points can also be viewed by clicking on the corresponding radio buttons.

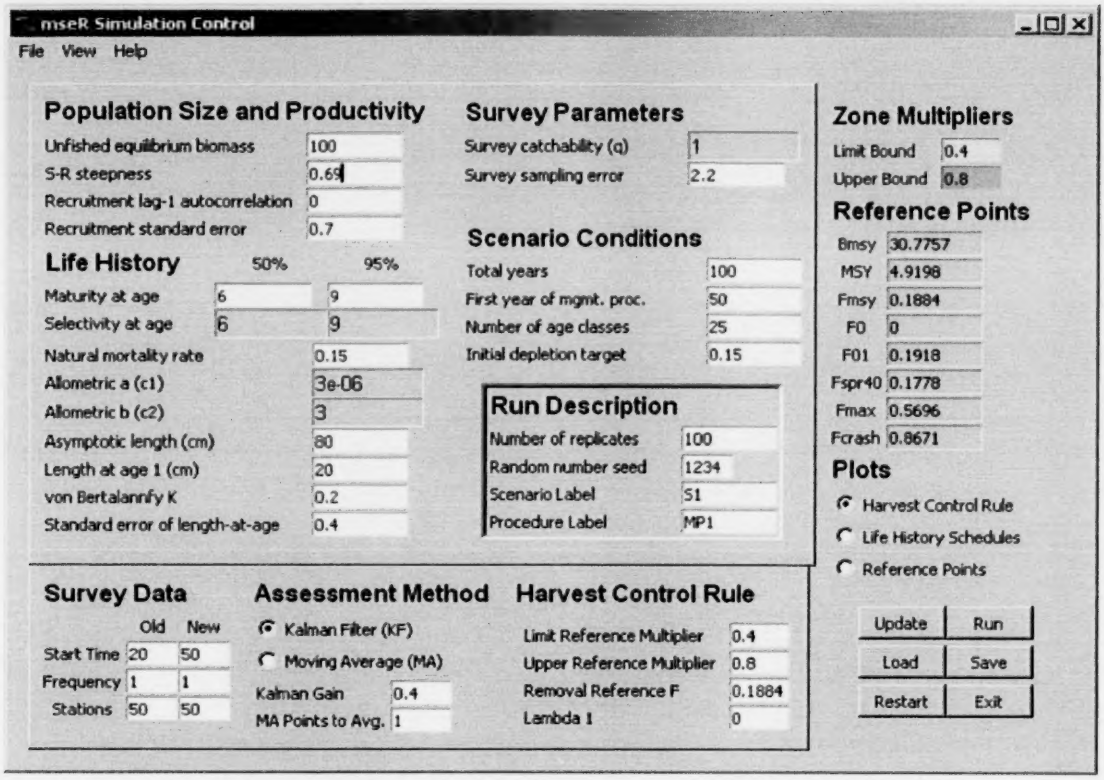

Figure 12. Specification of MP1 using the *mseR* Simulation Control GUI.

(4) Set the number of replicates to 100 and press the <Run> button to start the feedback control loop simulation.

(5) Repeat step 1 to 4 for the next three procedures to be tested (MP2, MP3, MP4). Note that the number of replicates for all subsequent simulations will need to be the same as those used in the first simulation set.

(6) Enter the command `guiView()` into the R console to open the *mseR* **Viewer Control** GUI. Use the arrow buttons to view plots for individual replicates from each of the four simulations that have been run.

(7) Enter the command `guiPerf()` into the R console to open the *mseR* **Performance Statistics Control** GUI.

(8) Click the "Select" check box next to all four saved simulations so that performance statistics plots for all four management procedures can be viewed at the same time.

(9) Use the *mseR* **Performance Statistics Control** plots and tabular outputs to answer the following questions related to the management objectives from Table 14. In some cases the Objective fields may have to be changed from the default setting, and range of plotting options may also be required, all of which are described in Section 5.4 of this report.

Conservation Objective (a) (Table 14):

Reach a target stock size of B_{MSY} with 90% certainty by 13 years (at simulation year 63).

1. Can the objective of reaching the target stock size be met in the 13-year time frame with 90% certainty?
2. How much does switching to a new harvest strategy affect the certainty that Conservation Objective 1a will be met if the old survey design is maintained?
3. How does this difference change if a new survey design is also implemented in year 51 of the simulation?

Depletion envelopes provided via the *mseR* **Performance Statistics Control** GUI are a useful tool for visualize tradeoffs in achieving objectives (Figure 13). The grey envelope in each figure panel shows 95% of the range of depletion levels over 100 simulations. The black line shows the median depletion level, while red lines represent the 10th and 90th percentiles of the distribution of depletion values at each time step. The large black dot on the right axis denotes the depletion level at B_{MSY} (~0.31) for a given scenario. In Figure 13, depletion envelopes compare performance of MP1 (50-station survey every year with the new harvest strategy) and MP3 (50-station survey every year with a constant F strategy) for the latter 50-years of simulation, i.e, the projection period. By setting the Objective entry fields in `guiPerf` to: Depletion = 0.31, Year = 63 and Certainty = 0.9, the ability of the new (MP1) and old harvest strategies (MP3) can be compared relative to the questions posed by the fishery team. Note that Year = 63 because the procedure is applied beginning at time tMP = 51, hence 13 years into the projection is simulation year 63.

Both harvest strategies fail to achieve the target biomass level of B_{MSY} with 90% certainty within the specified time frame of 13 years, or even over the entire 50-year projection period. Given the same annual 50-station survey, the new harvest strategy (MP1) performs more conservatively than the old constant F strategy (MP3). For example, under MP1 there is a 90% certainty the stock will be depleted to 0.215 of the unexploited level by year 13 of the projection whereas under MP3 there is a 90% certainty the stock will be more severely depleted to 0.176 of the unexploited level by year 13 of the projection. The certainty of achieving B_{MSY} by year 13 of the projection is 0.38 under MP1 and only 0.25 under MP3. However, this relative improvement in conservation performance will necessarily be at the expense of lower yields during some period of the projection.

The new survey design (150-station survey every 3 years) results in improved performance for procedures that use either the new (MP2) or old (MP4) harvest strategies

(Figure 14). However, both strategies are still unable to achieve the rebuilding target of B_{MSY} with 90% certainty by projection year 13. As was the case for the procedures that used a 50-station annual survey, the conservation performance of the new harvest strategy exceeds the old constant F strategy when using a 150-station survey. For example, there is a 66% certainty that B_{MSY} will be exceeded by year 13 for MP2 versus a 39% certainty for MP4.

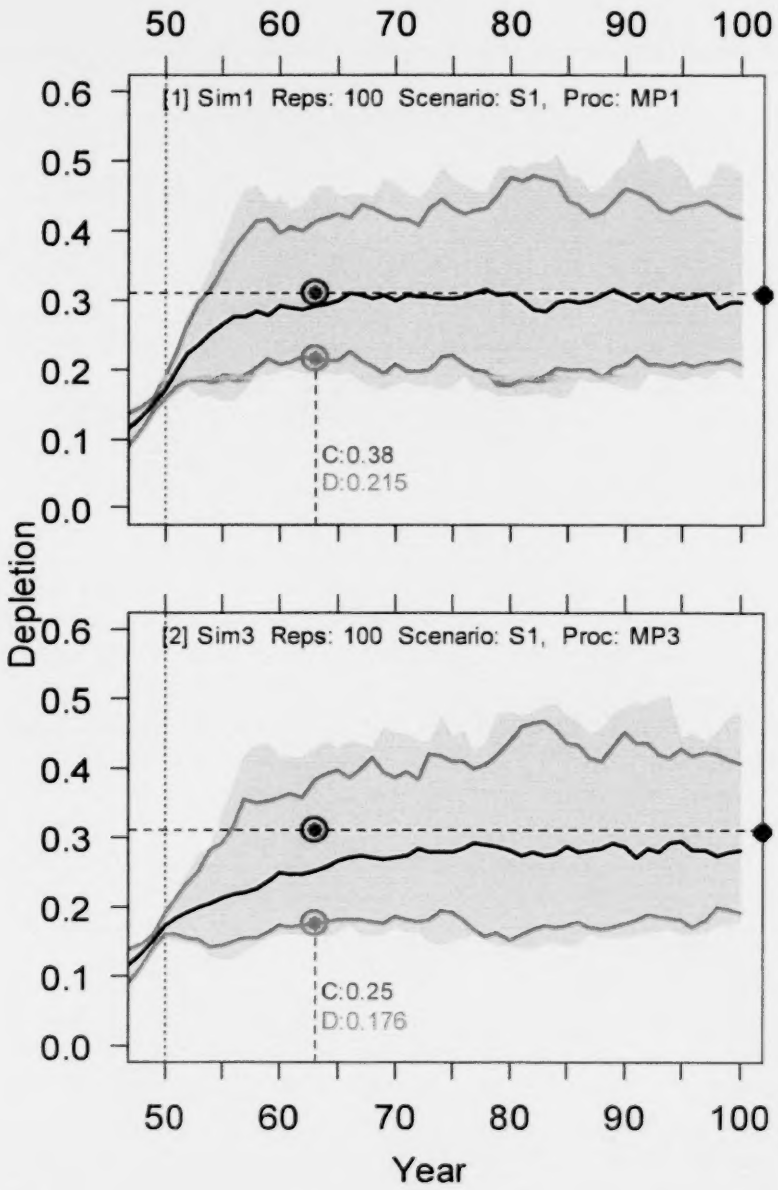

Figure 13. Depletion envelopes for MP1 and MP3 produced using the *mseR* **Performance Statistics Control** GUI.

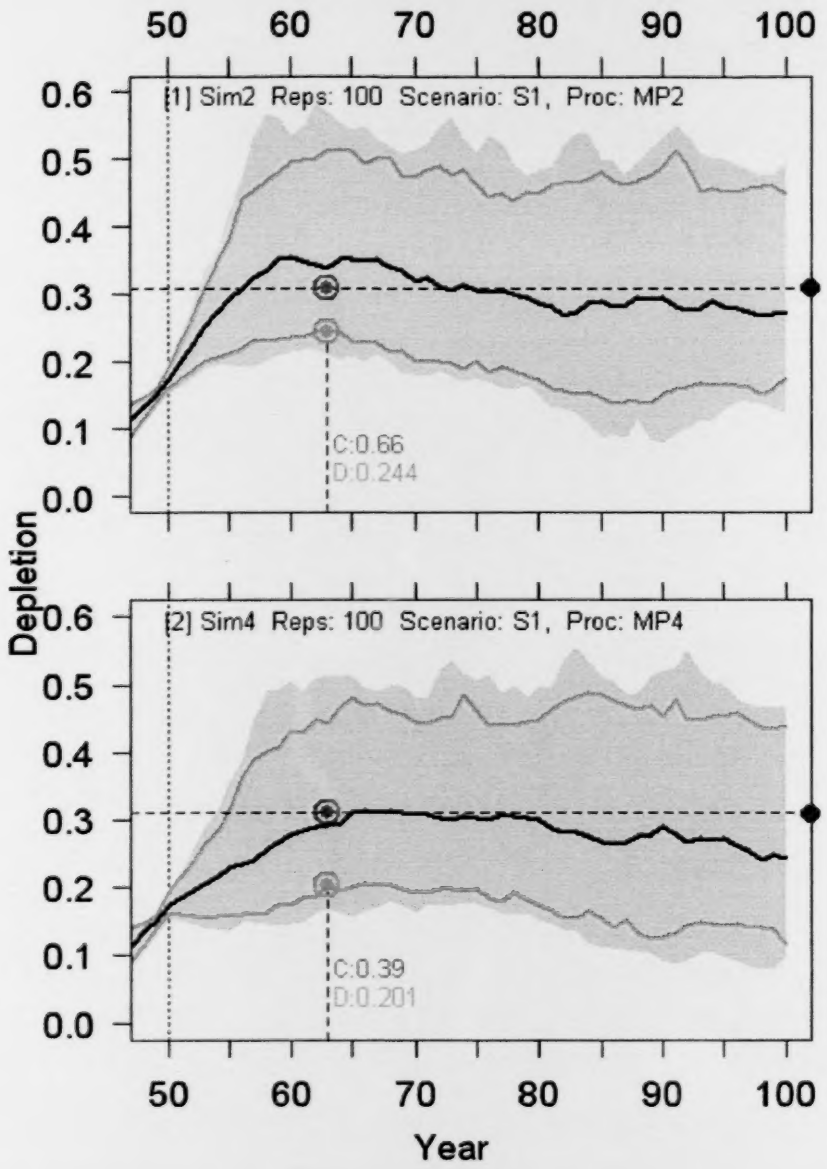

Figure 14. Depletion envelopes for MP2 and MP4 produced using the *mseR* **Performance Statistics Control** GUI.

Conservation Objective (c) (Table 14):

Avoid "Critical" stock sizes less than $0.5B_{MSY}$ with 95% certainty in each year.

1. Which of the four management procedures achieves Conservation Objective (c)?

The ability of management procedures MP1-MP4 to achieve Conservation Objective (c) is compared using the depletion envelopes shown in Figure 15. The black dot on the right axis of each figure panel shows the depletion level corresponding to B_{MSY} while the horizontal dashed line shows depletion at $0.5B_{MSY}$. In this figure the red lines denote the 5th and 95th percentiles of the depletion envelope, allowing one to focus on the interception of the horizontal dashed line at the target of $0.5B_{MSY}$ with the 5th percentile, i.e., 95% of the outcomes in a given year are above this line. Note that the Upper and Lower Quantile entry fields on the *guiPerf* interface were adjusted to 0.05 and 0.95, respectively, for this comparison. Avoiding the critical stock level of $0.5B_{MSY}$ with 95% certainty is more consistently achieved using annual 50-station surveys (MP1 and MP3) as opposed to using the 150-station survey every three years (MP2 and MP4). Of the four procedures, MP1 avoids the $0.5B_{MSY}$ level with at least 95% certainty over the entire projection period. This procedure, which uses the new harvest strategy, avoids breaching $0.5B_{MSY}$ with high certainty throughout most of the projection period. Procedures that use a 150-station survey every three years tend to breach the critical level by about year 80, or ~30 years into the projection period. The performance of MP1-MP4 against other stock and fishery objectives listed in Table 14 can be similarly evaluated using the outputs of the *mseR* **Performance Statistics Control** GUI.

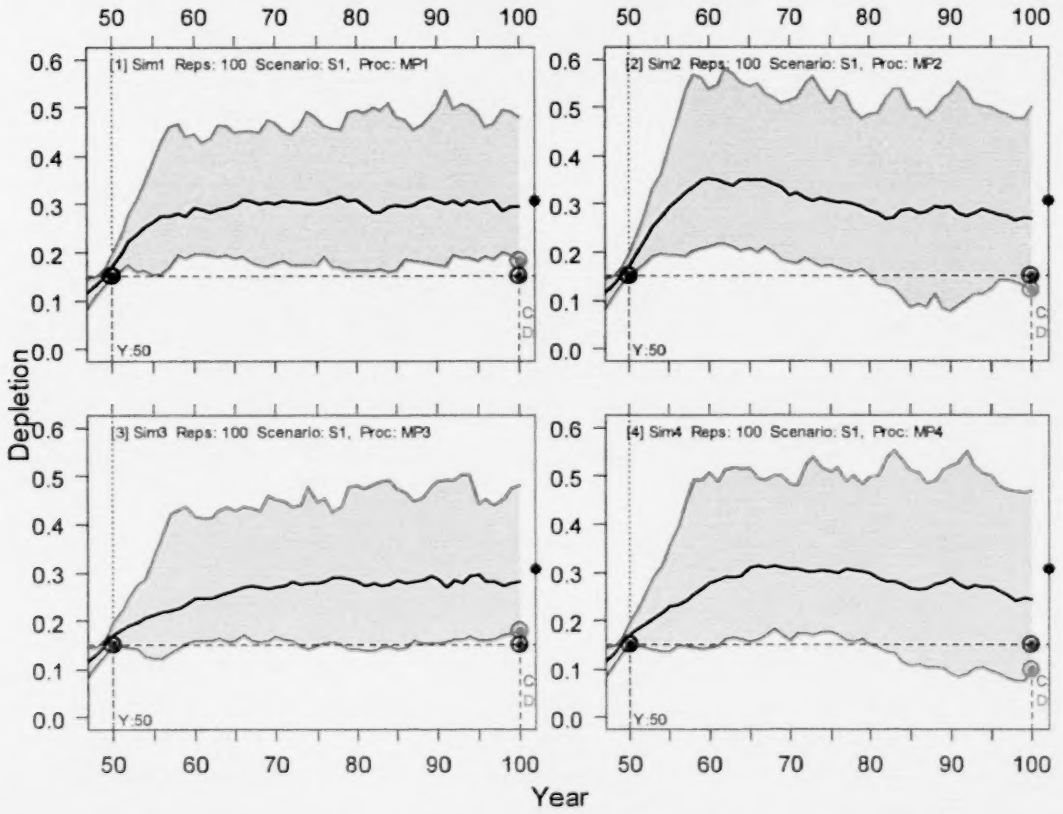
[1] Sim1 Reps: 100 Scenario: S1, Proc: MP1
[2] Sim2 Reps: 100 Scenario: S1, Proc: MP2
[3] Sim3 Reps: 100 Scenario: S1, Proc: MP3
[4] Sim4 Reps: 100 Scenario: S1, Proc: MP4
Y:50
Depletion
Year

Figure 15. Depletion envelopes for MP1, MP2, MP3 and MP4 produced using the *mseR* **Performance Statistics Control** GUI.

10 *mseR* FAQs

This section provides a list of frequently asked questions (Table 15) and descriptions of the software behaviour or solution to the problem listed.

Table 15. List of *mseR* Frequently Asked Questions (FAQs)

FAQ	Description
1	*mseR* GUI window disappears, where did it go?
2	How do I find the "hidden" *mseR* functions?
3	How do I ensure *mseR* functions are up to date?
4	How do I create a screen capture of a *mseR* GUI?
5	How do I copy a plot from an R graphics window?
6	Can I use *mseR* without the GUI?
7	Why aren't the entry fields on my *guiSim* GUI neatly aligned?
8	Why is the *mseRsimTracker.txt* file generating errors and failing to load?
9	Why does the *mseR* GUI look "cut-off" or display incorrectly?
10	Why are error messages coming from *PBS Modelling*?

(1) My *mseR* GUI window disappears, where did it go?

Schnute et al. (2010) noted that the R GUI normally runs as a Multiple Document Interface (MDI). This means that each "child" window, such as the R command-line console and graphics windows appear within the GUI itself. Usually there is a menu item that can be used to tile the sub-windows. The *PBS Modelling* software used to provide the graphical interface for *mseR* requires the *PBS Modelling* package which depends heavily on Dalgaard's (2001, 2002) R interface to the Tcl/*Tk* package (Ousterhout 1994). This interface combines a scripting language (**Tcl**) with a GUI toolkit (***Tk***). When combined with the MDI, windows generated by Tcl/*Tk* usually disappear when an application runs.

Lost GUI windows can be easily recovered by clicking the appropriate "***Tk***" icon on the Windows taskbar. Schnute et al. (2010) describe how the problem can be avoided by using the Single Document Interface (SDI) where the operating system manages all R windows independently on the Windows desktop. To switch to SDI, run the R GUI and choose <Edit> and <GUI Preferences> and then select and save the SDI option.

(2) How do I find the "hidden" *mseR* functions?

Functions in R can be hidden from the `ls()` command by defining the function with a dot as the lead character as in `.foo()`. To view these hidden files, use the R command `ls(all=TRUE)`.

(3) **How do I ensure *mseR* functions are up to date?**

A file called mseR.r is located in the working directory. To update all *mseR* functions enter `source("mseR.r")` at the R command console.

(4) **How do I create a screen capture of a *mseR* GUI?**

Any *mseR* GUI can be copied to the Windows Clipboard by clicking on the GUI, called getting focus, and then pressing <Alt> and <PrntScrn> simultaneously. After the GUI has been copied, the image can be pasted into a Microsoft Word or PowerPoint file via a "right-click" and <Paste> operation.

(5) **How do I copy a plot from an R graphics window?**

Any graph or picture that appears in an R graphics window can be copied to the Windows Clipboard by a "right-click" on the graphics window and then selection of <Copy as metafile> or <Copy as bitmap>. Alternatively, the contents of an R graphics window can be saved to a file by a "right-click" on the graphics window and then selection of <Save as metafile...> or <Save as bitmap...>.

(6) **Can I use *mseR* without the GUI?**

If you wish to develop your own graphing functions or summary statistics then the feedback simulation can be invoked directly using the R function called `runMSE`. See the section titled "The Closed-Loop Feedback Function: `runMSE`" in the manual for a description and the format of input and output files.

(7) **Why aren't the entry fields on my *guiSim* GUI neatly aligned?**

The version of the *PBS Modelling* package used to develop *mseR* did not allow entry fields to be ghosted, or greyed-out, to make them unavailable for editing. This feature has been added to the *PBS Modelling* package in subsequent versions. This ability is mimicked using a grey text box to give the impression of an option that is unavailable, however, choice of font for text boxes is different than those used for entry fields in *PBS Modelling*, so that the amount of space used varies depending on the current resolution of the display. Thus, the entry fields may be unevenly aligned on some displays. *mseR* was developed at a display resolution of 1650 by 1080 pixels.

(8) **Why is the *mseRsimTracker.txt* file generating errors and failing to load?**

The tracking file can be edited by a user. If the user destroys the integrity of the file by inserting extra line feeds, omitting commas, or violating other tracking file rules then the file will not load correctly.

(9) **Why does the *mseR* GUI look "cut-off" or display incorrectly?**

On very few occasions, *mseR* GUIs have displayed incorrectly. This is believed to be a graphics card driver issue with Tcl/*Tk* and has occurred only on laptop computers to date. The problem was resolved by closing the GUI with the "X" at the top right corner of the GUI and re-entering the GUI command.

(10) **Why are error messages coming from *PBS Modelling*?**

When users try to run `guiSim()`, complaints related to *PBS Modelling* functions may appear in the R command-line console such as "`CloseActWin not found`". These errors mean that *PBS Modelling* is not installed or that an error occurred during installation. Repeat the R package installation steps and retry `guiSim()`. The *PBSmodelling* directory may have to be deleted from the R directory under *Program Files\R\R2.x.x\Library* before attempting to re-install the package.

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Appendix A Age-structured Survey and Fishery Operating Model

This appendix presents the model notation (Table A-1) and equations (Table A-2) for the age-structured survey and fishery operating model implemented by *mseR*. Operating model equations are prefixed by "O", e.g., Eq. O.3.

The population at time $t = 1$ is initialized in the deterministic, unfished equilibrium state using Equations (O.9)–(O.11). State dynamics are driven by recruitment and fishing mortality rate, F; other factors are held constant. In calculating the catch equation (O.17), F and natural mortality rate, M, are assumed to operate continuously and simultaneously throughout the year. The simulation time-frame is divided into an initialization, ($t \le T_1 - 1$) and a projection $T_1 \le t \le T_2$ period. Stock status at $t = T_1 - 1$, just prior to the projection period, is initialized at a predetermined level of spawning biomass by solving for the $T_1 - 1$ F s that maximize the cumulative catch over $1 \le t \le T_1 - 1$ subject to the constraint that realized depletion $d = B_{T-1}/B_0$ is approximately equal to a pre-specified level d^*. This optimization step involves maximizing the objective function:

$$G(\mathbf{F}') = \sum_{t=1}^{t=T_1-1} D_t - 1000\left(d - d^*\right)^2 \quad .$$

The time needed to solve this optimization was limited by: (*i*) specifying a reduced set of n fishing mortality parameters $F' = \left(F'_1, F'_2, \ldots, F'_n\right)$ corresponding to a uniformly spaced grid of n points in time between $t = 1$ and $t = T_1 - 1$; (*ii*) using a cubic spline interpolation of these n points to generate the complete fishing mortality history at all t, namely $F' = \left(F_1, F_2, \ldots, F_{T-1}\right)$, and (*iii*) performing the optimization with respect to F'. In most cases, a convergence tolerance of 0.0001 on G gives realized depletion values that are within 0.01–0.03 of the pre-specified level using n=5. During the projection period, the harvest control rule determines the TAC. Both D_t and F_t are computed by solving the catch equation (O.17) for the given exploitable biomass and M. Simulated surveys, Equation (O.20), generate the estimates of the absolute spawning and exploitable biomass at the beginning of the year. A lognormal distribution of random survey observation errors is determined by the standard error τ of log-survey residuals.

Note that stochastic variation in recruitment during the initialisation period will result in different trends in population size around the time that new survey and management procedures are implemented (i.e., $t = T_1$). For example, in some cases, a series of weak recruitment years combined with moderate fishing may result in a low and declining stock abundance by year $T_1 - 1$, while in other cases the stock may be in a low state but increasing at $T_1 - 1$ due to a series of good recruitments.

The equilibrium calculations presented in Table A-3 are sufficient to compute any of the following reference fishing mortality rates via optimisation or root-finding algorithms:

$F_{0.1}$ fishing mortality rate where the slope of yield-per-recruit (E.3) is 10% of the slope at the origin;

F_{max} fishing mortality that maximizes yield-per-recruit (E.3);

$F_{X\%}$ fishing mortality that reduces spawning stock biomass-per-recruit (E.4) to X% of the unfished level;

F_{crash} fishing mortality that reduces equilibrium spawning biomass (E.6) to zero;

F_{MSY} fishing mortality that maximizes equilibrium total yield (E.7).

Recruitment, spawning biomass, and yield reference points are obtained by substituting the corresponding reference fishing mortality rates for $\tilde{F}$ in E.1 and computing E.5-7. For example, biomass at maximum sustained yield, B_{MSY}, is obtained by setting $\tilde{F} = F_{MSY}$.

Table A-1. Notation for the age-structured population, survey and fishery operating model. The "Symbol" column gives notation used in subsequent equation tables and "Names" provide the actual variable names used in the R computer code when they exist.

Symbol	Name	Value	Range	Description
T_0		$T_1/2$		Mid-point of initialisation period
T_1	tMP	20	$T_1 > 1$	Year when the management procedure begins
T_2	nT	100	$T_2 > T_1$	Total number of years to simulate
A	nAges	25	$A > 2$	Number of age-classes
t	t		1,2,...,T	Time step
a	age		1,2,...,A	Age-class in years
B_0	B0	100	$B_0 > 0$	Unfished spawning biomass (1,000s tonnes)
h	rSteepness	0.65	$0.2 < h < 1.0$	Recruitment function steepness
M	M	0.15	$M > 0$	Instantaneous natural mortality rate (/yr)
L_∞	Linf	80.0	$L_\infty > 0$	Asymptotic length (cm)
L_1	L1	40.0	$L_1 < L_\infty$	Length-at-age 1 (cm)
k	vonK	0.20	$0 < k < 1.0$	von Bertalanffy growth constant
a_{50}	aMat50	5	$a_{50} > 1$	Age-at-50% maturity
a_{95}	aMat95	8	$a_{95} > a_{50}$	Age-at-95% maturity
q	qSurvey	1.0	$q > 0$	Survey catchability coefficient
σ_R	sigmaR	0.70	$\sigma_R \geq 0$	Standard error of log-recruitment
σ_L	sigmaL	0.40	$\sigma_L \geq 0$	Standard error of length-at-age
γ_R	gammaR	0.0	$-1 \leq \gamma_R \leq 1$	Lag-1 autocorrelation in log-recruitment deviations
τ	tau	2.30	$\tau > 0$	Survey spatial factor
R_0	R0			Unfished recruitment
m_a	mat			Proportion mature-at-age
w_a	wtAge			Weight-at-age (kg)
ϕ	phi			Unfished equilibrium spawning biomass per recruit
$N_{a,t}$	Nat			Number of age a fish in year t
$B_{a,t}$	Bat			Biomass of age a fish in year t
B_t	Bt			Spawning biomass in year t
N_t	Nt			Spawning numbers in year t

Symbol	Name	Value	Range	Description
I_t	`It`			Survey biomass estimate
$\omega_{R,t}$	`omegaRt`			Auto-correlated log-normal recruitment residual
δ_t	`deltat`	$N(0,1)$		Uncorrelated log-recruitment residual
ε_t	`epsilont`	$N(0,1)$		Uncorrelated log-survey residual
C_t	`Ct`			Fishery catch numbers
D_t	`Dt`			Fishery catch biomass

Table A-2. Age-structured population, survey, and fishery operating model. This table defines the population and fishery dynamics for a given set of input parameters Θ. Fishery catches D_t during the New period are determined using the management procedure and harvest control rule defined in Appendix B.

Parameters

O.1 $$\boldsymbol{\Theta} = \left(B_0, h, \boldsymbol{\delta}, q, \boldsymbol{\sigma}, \tau, \gamma, L_\infty, L_1, k, M, a_{50}, a_{95}\right)$$

Life history schedules

O.2 $$l_a = L_\infty + \left(L_1 - L_\infty\right) e^{\left(-k(a-1)\right)}$$

O.3 $$w_a = c_1 l_a^{c_2} \left(1 + 0.5 c_2 (c_2 - 1)\sigma_L^2\right)$$

O.4 $$m_a = \frac{1}{1 + \exp\left[-g\left(a - a_{50}\right)\right]}, \text{ where } g = \log(19) / \left(a_{95} - a_{50}\right)$$

Stock-recruitment relationship

O.5 $$\phi = \sum_{a=1}^{A-1} e^{-M(a-1)} m_a w_a + \frac{e^{-M(A-1)} m_A w_A}{1 - e^{-M}}$$

O.6 $$R_0 = B_0 / \phi$$

O.7 $$a = \frac{4hR_0}{B_0\left(1 - h\right)}$$

O.8 $$b = \frac{5h - 1}{B_0\left(1 - h\right)}$$

Initial population

O.9 $$N_{a,1} = R_0 e^{-M(a-1)}, \qquad 1 \le a \le A - 1$$

O.10 $$N_{A,1} = N_{A-1,1} \Big/ \left(1 - e^{-M}\right)$$

O.11 $$B_{a,1} = N_{a,1} w_a$$

State dynamics

O.12 $$\omega_{R,t} = \begin{cases} \dfrac{\sigma_R}{\sqrt{1 - \gamma_R^2}} \delta_t & t = 1 \\ \gamma_R \omega_{R,t-1} + \sigma_R \delta_t & t > 1 \end{cases}$$

O.13 $$N_{1,t} = \frac{a B_{t-1}}{1 + b B_{t-1}} \exp\left[\omega_{R,t} - 0.5\sigma_R^2 \Big/ \left(1 - \gamma_R^2\right)\right]$$

O.14 $$N_{a,t} = N_{a-1,t-1} e^{-M + m_a F_{t-1}} \quad , \qquad 2 \le a \le A-1$$

O.15 $$N_{A,t} = N_{A-1,t-1} e^{-M + m_{A-1} F_{t-1}} + N_{A,t-1} e^{-M + m_A F_{t-1}}$$

O.16 $$B_t = \sum_{a=1}^{A} m_a w_a N_{a,t}$$

O.17 $$C_{a,t} = \frac{m_a F_t}{M + m_a F_t} \left(1 - e^{-m_a F_t}\right) N_{a,t}$$

O.18 $$D_t = \sum_{a=1}^{A} C_{a,t} w_a$$

O.19 $$F_t = \begin{cases} \left(M / 2T_1\right)\left[2h_1'\left(T_1 - \left|2t - T_1\right|\right) + h_2'\left(\left|2t - T_1\right| + 2t - T_1\right)\right] & t \le T_1 - 1 \\ D_t - \sum_a C_{a,t} w_a = 0 & t \ge T_1 \end{cases}$$

Survey observations

O.20 $$I_t = qB_t \exp\left[\varepsilon_t - 0.5\sigma_S^2\right]$$

Table A-3. Equilibrium functions of a fishing mortality rate $\tilde{F}$.

Equation	Formula	Description
E.1	$\Omega = \left(\tilde{F}, \Theta\right)$	parameters
E.2	$\ell_a = \begin{cases} 1 & a = 1 \\ \ell_{a-1} e^{\left(-M - m_{a-1}\tilde{F}\right)} & 2 \le a < A \\ \ell_{A-1} e^{\left(-M - m_{A-1}\tilde{F}\right)} \Big/ \left(1 - e^{\left(-M - m_A \tilde{F}\right)}\right) & a = A \end{cases}$	survivorship to age a
E.3	$\phi_y = \sum_{a=1}^{A} \ell_a m_a w_a \tilde{F} \left(1 - e^{\left(-M - m_a \tilde{F}\right)}\right) \Big/ \left(M + m_a \tilde{F}\right)$	yield per recruit
E.4	$\phi_{ssb} = \sum_{a=1}^{A} \ell_a m_a w_a$	spawning stock biomass per recruit
E.5	$\tilde{R} = \left(a\phi_{ssb} - 1\right) / b\phi_{ssb}$	equilibrium recruitment
E.6	$\tilde{B} = \tilde{R}\phi_{ssb}$	equilibrium spawning stock biomass
E.7	$\tilde{C} = \tilde{B} \frac{\tilde{F}}{M + \tilde{F}} \left(1 - e^{-\tilde{F}}\right)$	equilibrium total yield

Appendix B Harvest Control Rule

A harvest control rule (HCR) translates the outputs of a stock assessment method into a management regulation, often as a total allowable catch (TAC) or effort control. The simulated fishery during the new period is assumed to be managed using an output control approach based on setting annual TACs. The HCR for calculating these limits contains two main elements, namely (*i*) a formula for translating perceived stock status into a target fishing mortality and (*ii*) a smoothing term that can be used to control year to year volatility in catches (Table B-1). The target fishing mortality rate (F_t) is determined by a stock assessment estimate of harvestable biomass $\hat{B}_t$ and the DFO (2006) harvest strategy (H.1) in which the Limit Reference Point (B_{lim}) and Upper Stock Reference (B_{upper}) are multiples of a B_{MSY} biomass reference. This choice is specific to the *mseR* implementation, but any reference indicator of "Stock Status" such as $B_{40\%}$ could also be used. DFO (2006) and Shelton and Sinclair (2008) explain that estimated stock biomasses greater than B_{upper} are considered "healthy" and are therefore exploited at the Removal Reference fishing mortality rate. Choices for the removal reference may be F_{MSY}, $F_{0.1}$, $F_{40\%}$, or any other reference fishing mortality rate (e.g., those listed in Appendix A. The target fishing mortality rate is reduced linearly as the estimated stock declines from B_{upper} to B_{lim} and is set to $F_t = 0$ when the estimated stock is below B_{lim}.

However, it is important to note that the Limit Reference Point and Upper Stock Reference cannot be used to simultaneously determine F_t and delineate regions of stock status. Harvest control rule reference points and stock status zones, which actually represent required elements of measurable objectives, must be independent if the harvest control rule is to effectively contribute to achieving an acceptable trade-off between conservation and yield objectives. As a contrary example, by setting B_{lim} and B_{upper} both nearly zero, F_t becomes independent of Stock Status (i.e., a constant F policy) and essentially all biomass levels greater than zero would lie above the Upper Stock Reference point. Therefore, a Limit Reference Multiplier (LRM > 0) and Upper Stock Multiplier (USM > LRM) are used to set the "break points" of the harvest rule where fishing mortality is adjusted independently from the reference points used to delineate the Critical-Cautious and Cautious-Healthy boundaries. The multipliers set the break points relative to the chosen base biomass level (e.g., B_{MSY}). For example, the lower and upper break points of the HCR could be set at $0.4B_{\text{MSY}}$ and $0.8B_{\text{MSY}}$ using LRM=0.4 and USM=0.8, respectively. This choice produces the special case where the HCR break points align with the provisional boundaries of the Critical-Cautious and Cautious-Healthy zones suggested in the DFO Decision-making Framework (http://www.dfo-mpo.gc.ca/fm-gp/peches-fisheries/fish-ren-peche/sff-cpd/precaution-eng.htm).

The second component of the harvest control rule is a smoother that takes a weighted average of the quota in year t - 1 and the quota in the current year t as suggested by the harvest control rule (H.3). The parameter $0 \leq \lambda_1 < 1$ represents the fraction of previous year's quota to apply in the quota calculation for year t. Such a blending of adjacent quotas provides a way to control inter-annual variability in yield. However, it is

critical to evaluate such *ad hoc* adjustments because blending quotas increases the lag time between real abundance changes of the stock and management responses. Poor choices for λ_1 may increase the risk of destabilizing the feedback management system, possibly leading to stock collapse.

Table B-1. Harvest control rule component of the simulated management procedure. Calculation of the target removal rate F_t' implements the DFO (2006) precautionary harvest policy, while calculation of the quota D_t includes a dampener (λ_1) on the magnitude of year-to-year volatility. Specific notation for each calculation is given in the right column.

H.1	$\Psi = \left(\hat{B}_t, F_{\text{ref}}, B_{\text{lim}}, B_{\text{upper}}, \lambda_1, D_{t-1}\right)$	Rule parameters
H.2	$F_t' = \begin{cases} 0 & \hat{B}_t < B_{\text{lim}} \\ F_{\text{ref}}\left(\dfrac{\hat{B}_t - B_{\text{lim}}}{B_{\text{upper}} - B_{\text{lim}}}\right) & B_{\text{lim}} \le \hat{B}_t < B_{\text{upper}} \\ F_{\text{ref}} & \hat{B}_t \ge B_{\text{upper}} \end{cases}$	B_{lim} limit reference point B_{upper} upper stock reference F_{ref} removal rate reference F_t' target removal rate $\hat{B}_t$ biomass estimate
H.3	$D_t = \lambda_1 D_{t-1} + (1-\lambda_1)\dfrac{F_t'}{M + F_t'}\left(1 - e^{-M-F_t'}\right)\hat{B}_t,$	D_t catch in year t λ_1 weight (0,1) given to D_{t-1}

Appendix C Performance Statistics

Monte Carlo simulation models can provide *state*, *duration*, and *probabilistic* indicators of fisheries management procedure performance. State measures provide a view of the system state(s) at a single point in time, which is useful for measuring performance against pre-defined targets. Duration indicators are useful for measuring how long certain conditions might last, or how long until some state is reached. Both state and duration indicators are random variables in Monte Carlo simulations, so a complete performance summary must also specify the probability level at which to measure an indicator. For example, in fisheries simulations as implemented by *mseR*, the stock size relative to B_{MSY} is an indicator of both conservation and economic performance that can be measured according to: (*i*) state - the biomass at a given time for some probability, which can then be compared to B_{MSY}; (*ii*) duration - the time it takes to reach B_{MSY} for some pre-specified probability; or (*iii*) the probability of reaching B_{MSY} by some pre-specified time.

Performance statistics include average annual catch; average, final, and lowest depletion over some time period t_1 - t_2; average annual variation in catch, median proportion of years in Critical, Cautious, and Healthy zones; probability of stock status greater than B_{MSY}; time to achieve a pre-specified depletion at a pre-specified probability; the depletion level at a pre-specified time and probability level; the probability of achieving a pre-specified depletion by a pre-specified time. The last three measures are inter-related, but are required to address particular questions. The term "pre-specified probability" means that particular upper and lower quantiles of the distribution of statistics are chosen in a performance specification. For depletion, catch, and catch variability measures, the medians, lower, and upper quantiles are provided. Table C-1 provides the details for selected performance statistics.

Performance measures related to stock status are compared to Critical, Cautious, and Healthy zones of Stock Status as defined in DFO (2006). Two Zone Multipliers are used to delimit these regions. For example, the Critical-Cautious zone boundary can be set to $0.5B_{MSY}$ and the Cautious-Healthy boundary to $1.0B_{MSY}$ to represent stock status objectives or benchmarks. Maintaining the stock above the Critical zone 95% of the time, and in the Healthy zone at least 50% of the time is suggested by Shelton and Sinclair (2008), as a good starting point.

Table C-1. Definitions of selected performance statistics used to evaluate alternative management procedures. The time interval $t = t_1,\ldots,t_2$ defines the time window within the New survey projection period over which statistics are computed.

	Symbol	Definition	Description
P.1	AAV	$AAV = \sum_{t=t_1}^{t_2} \lvert C_t - C_{t-1} \rvert \Big/ \sum_{t=t_1}^{t_2} C_t$	Average annual absolute change in the catch over the time interval, where C_t is the catch biomass in year t.
P.2	$\overline{D}$	$\overline{D} = \frac{1}{t_2 - t_1 + 1} \sum_{t=t_1}^{t_2} \left(\frac{B_t}{B_0} \right)$	Arithmetic mean of annual depletion.
P.3	$P_{critical}$	$P\left(B \le B_{\text{lim}}\right)$	Proportion of years that true spawning biomass is at or below the Critical-Cautious zone boundary
P.4	$P_{cautious}$	$P\left(B_{\text{lim}} < B < B_{\text{upper}}\right)$	Proportion of year that true spawning biomass is in the Cautious zone
P.5	$P_{healthy}$	$P\left(B \ge B_{\text{upper}}\right)$	Proportion of years that true spawning biomass is at or above the Healthy zone